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Stratigraphic Controls on Tight-gas Sandstone: Insight from a Regional Outcrop-to-Subsurface Sequence-stratigraphic Framework of the Upper Williams Fork Fm., Piceance Basin, CO

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Stratigraphic Controls on Higher-than-average Permeability Zones in Tight-gas Sandstones, Williams Fork Fm. Piceance Basin, CO

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Abstract

The Piceance Basin, CO is a type locale for unconventional tight-gas sandstone in the Rocky Mountains (Law, 2002). Productive Williams Fork sandstones are extremely heterogeneous fluvial to marginal marine reservoirs that have very low permeability (<0.1 md) that typically require expensive hydraulic fracturing with 10 - 20 acre well spacing to produce. Despite the enormous gas potential of the Piceance Basin many wells can be uneconomic unless higher permeability fairways are found. Although many new completion and stimulation technologies have vastly improved production, higher-than-average permeability zones that result from improved matrix porosity and/or natural fracture systems are needed to ensure economic wells. Geologic controls on higher-than-average permeability zones are complex and poorly understood; these controls include controls on reservoir quality, fracture development and compartmentalization such as depositional environment, diagenesis, mechanical rock properties and strain. This study presents a regional sequence-stratigraphic framework that integrates outcrop and subsurface data to better understand the stratigraphic controls on tight-gas sand production. Improved understanding of the regional stratigraphic framework provides the foundation for predicting "sweet spots" in tight-gas sandstone reservoirs.

The integration of 17 stratigraphic profiles, detailed facies analysis, detrital composition, paleocurrent data, synthetic GR curves from hand-held spectrometer and 104 well logs delineated key stratigraphic stacking patterns and sequence-stratigraphic surfaces that were correlated into the subsurface at a basin-scale. Thirty-four facies defined five main cycles within the predominantly fluvial to paludal lower Williams Fork Formation: (1) Cycle A-Tidal/coastal plain to single-story meandering fluvial, (2) Cycle B-Tidal/coastal plain to vertically-stacked meandering fluvial with floodplain, (3) Cycle C-single-story, meandering fluvial with undifferentiated floodplain to vertically-stacked meandering fluvial, (4) Cycle D-Tidal/coastal plain to anastomosed fluvial complex, and (5) Cycle E-Anastomosed fluvial complex to single-story, meandering fluvial with undifferentiated floodplain.

Based on radiometrically constrained ammonite data, the total time duration of the study interval is estimated at 1.5 My (75.08 Ma to 73.52 Ma). Six complete, high-frequency (4^{th} order) depositional sequences were identified with an estimated duration of 260 ky each in the lower Williams Fork and Rollins Sandstone. The higher-frequencey sequences build into two sequence sets. An older, retrogradational to aggradational (i.e., transgressive) sequence set A consists of

more poorly connected anastomosed fluvial, tidal-fluvial and paludal sandstones, whereas the younger progradational to aggradational (i.e., highstand to lowstand) sequence set B consists of cycles of better connected, sandier meandering fluvial anastomosed.

Isopach maps of sequence set A (older sequence set) shows thickening to the east and northeast with thinning to the west (toward the Douglas Creek Arch, DCA) and southwest (toward the Uncompahgre Uplift, UU) suggesting that the DCA and Uncompahgre were affecting sedimentation during the lowermost Williams Fork but the Uinta Mountains had little affect. The younger sequence set B shows thinning toward the UM in the northwest, truncation and growth-strata development along the DCA in the west, and thinning toward the UU in the south, suggesting that the DCA, UU and UM were active and affecting sedimentation during the upper part of the lower Williams Fork. Net-sandstone maps support thickening trends to the east and northeast showing sandier successions concentrated near known productive natural gas fields and potential new areas.

Five facies associations where identified within the lower Williams Fork with the best reservoir potential for matrix porosity, but may also have unique mechanical properties (i.e., thickness, lateral extent, composition etc) that control fracture development in different stratigraphic and/or geographic areas. From best to worst the reservoir types include: (1) upper shoreface-foreshore, (2) anastomosed fluvial complex, (3) multi-story, vertically-stacked meandering fluvial channels, (4) single-story meandering fluvial channels, (5) tidal channels within incised valleys. These reservoir types are systematically partitioned within the sequence-stratigraphic framework such that reservoirs with higher matrix porosity are typically clustered in the highstand to lowstand sequence-set and the worst quality reservoirs are in the transgresssive sequence set.

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1.0 Introduction

The Piceance Basin, in northwest Colorado, is a world-renowned, unconventional tight-gas sandstone from the Rocky Mountain region (Figure 1.1). Tight-gas sandstones are characterized as reservoirs with permeabilities less than 0.1 md and be associated with basin-centered gas accumulations (BCGA) (Meckel and Thomasson, 2008). The primary, tight-gas petroleum system in the Piceance Basin consists of the following: the source rock for the Piceance Basin lies within the Mesaverde Group and is associated with three main stratigraphic intervals: marine shales within the Mancos Shale and Iles Formation, coals within the Iles and Williams Fork formations, and nonmarine shales within the Iles and Williams Fork formations (Yurewicz et al., 2003). Yurewicz et al. (2003) and Cumella and Scheevel (2008) concluded that the coals within the Iles and Williams Fork formations have generated the largest volume of gas based on burial history models and geochemical properties. Geochemical characteristics of the Mesaverde Group consist of the following: waxy, terrigenous (type III) oil types, high saturated/aromatic hycrocarbon values (approximately -26.0/-28.0), and greater than 3.5 pristane/phytane (pr/ph values) (Lillis et al., 2003). The results from Lillis et al. (2003) are indicative of coal and/or units with high coal organic matter and concur with the results from Yurewicz et al. (2003), that the main source rock for the Mesaverde Group lies within the coaly-coastal plain environments within the Williams Fork and Iles formations within the Piceance Basin. The thermal maturation and generation of oil and gas is the next part of the petroleum system. After burial of these source rocks (depths reaching over 13000 ft in some areas of the basin), vitrinite reflectance (Ro) values can exceed 1.35% with high Ro values reaching up to 2.1% (Johnson and Roberts, 2003). Maximum temperatures (Tmax), another geochemical parameter ranges from 430-478 degrees Celsius in this basin. Based on Peters and Cassa (1994), Tmax values ranging from 435-470 degree Celsius are indicative as thermally mature. Generated gas from coal and carbonaceous shale then migrated to nearby, low-permeability, tight-sandstone fluvial reservoirs within the Campanian aged strata within the Mesaverde Group (Iles and Williams Fork formations which are applicable to this study) (Johnson and Roberts, 2003; Pranter et al., 2009). Migration of hydrocarbons has mainly been attributed to pathways formed by natural fractures due to over-pressured conditions, which help prop open fractures, increasing gas production in the basin (Johnson, 1989). Cumella and Scheeval (2008) elastic versus pore-pressure gradient models show that increasing pore-pressure gradients, typically closer to the gas-bearing coals, have high fracture densities. Trapping mechanisms for the Mesaverde Group consist of capillary seals as well as isolated and compartmentalized reservoirs within the basin-centered gas accumulation (BCGA) (Masters, 1979, Johnson, 2003). Lacustrine shale within the overlying Green River Formation, Eocene age, acts as a regional seal overlying the Mesaverde Group petroleum system (Johnson and Roberts, 2003). The present study focuses on tight-gas reservoirs within the Rollins Sandstone Member of the Iles and lower Williams Fork formations) (see Figure 1.2).

Although not all unconventional tight-gas plays are associated with basin-centered gas accumulations (BCGA), many of these plays are still found within BCGA's (Figure 1.1). BCGA's are pervasive gas accumulations that are abnormally pressured (over- or under-pressured), and have low permeability reservoirs (less than 0.1mD), typically lacking down dip water contacts (Law, 2002; Meckel and Thomasson, 2008). In continuous BCGA's, not all of the basin will be productive due to low permeabilities, temperatures, pressures, and burial depths. Therefore, it is essential to explore for "sweet-spots" or zones of higher pressures, thicknesses, fracture densities, and better reservoir quality (higher porosities/permeability from facies and/or diagenesis). Compiled historical data for cumulative production of the Mesaverde Group reveals over 724 billion cubic feet of gas (BCFG) in the Piceance Basin (Cluff and Graff, 2003). The discontinuous, compartmentalized, and heterogeneous nature of these fluvial deposits is why much of the basin is produced at 10-20 acre well spacing and contributes to the complications that arise when correlating in the basin, especially when using sequence stratigraphy.

Although there has been significant work and advancements in producing tight-gas sandstone plays in the Piceance Basin (i.e., hydraulic fracturing, increase well spacing densities), there are many unresolved geologic questions which remain. Specifically, understanding the regional sequence-stratigraphic framework and the distribution of good-quality facies within this framework provides insight into the stratigraphic controls on "sweet-spots". However, complexities with correlating through nonmarine strata have plagued many basins, including the Piceance.

The main controls to consider when constructing a sequence-stratigraphic correlation are base level (an equilibrium surface where neither erosion nor deposition occur commonly associated with relative sea level), tectonics, climate, and sediment supply (Shanley and McCabe, 1994). Base-level changes and/or tectonics affect accommodation and the rate at which accommodation changes in relation to sediment supply affect facies stacking patterns and stratigraphic architecture. Jervey (1988) defined accommodation as the amount of space available for sediments to accumulate which is measured between base level and the depositional surface. Simultaneously, the development of the concept of accommodation was applied to both nonmarine and marine strata and showed that other controls (tectonics, eustasy, and climate) can influence accommodation as well. Accommodation to sediment supply relationships are illustrated through the work of Shanley and McCabe (1994) which state the following: (1) an increasing rate of accommodation yield stacking patterns of retrogradational (sediment supply < accommodation), aggradational (sediment supply = accommodation), and progradational (sediment supply > accommodation) (2) zero accommodation yields sediment bypass, and finally (3) loss of accommodation is represented by regional incision. Understanding how these controls (which are more easily observed in nearshore settings) relate to correlative continental fluvial-dominated successions, is important if sequence stratigraphy is to be applied to terrestrial settings. The stacking patterns and facies cycles within fluvial successions, for example, can present challenges such as identifying flooding surfaces. Previous works from Shanley et al. (1992), Hettinger and Kirschbaum (2003), Aschoff (2008), Aschoff and Steel (2011a, b), Gomez-Veroiza and Steel (2010), Thompson (2011), Steel et al. (in press) and others have shown detailed high-frequency flooding surfaces and/or tidal influences 10-100 km from paleoshorelines. These surfaces and signatures can be correlated regionally into more fluvial successions and are key criterion for identifying non-Waltherian, landward shifts which aid sequence-stratigraphic correlation (Shanley and McCabe, 1994).

Unfortunately, within fully nonmarine successions, tidal signatures are not always preserved or present in outcrop. Therefore recognizing stacking patterns in fluvial strata becomes critical to understand accommodation. Eustasy, tectonics, and climate all affect accommodation in continental settings; however the roles of eustasy tend to decrease further inland (Shanley and McCabe, 1994). The fluvial facies stacking patterns help interpret what was occurring at the time of deposition (i.e., within a fully nonmarine succession with predominately anastomosed fluvial complexes and high concentrations floodplain and crevasse splay deposits, could be indicative of a rise in base level or increase in accommodation, perhaps around a nearby uplifting structure). Previous studies on the Williams Fork Formation show that it is typically concentrated into one general association: alluvial/nonmarine-fluvial (Johnson, 1989 and Hettinger and Kirschbaum, 2002 and 2003). Patterson et al. (2003) and Shaak (2010) have applied sequence stratigraphy within the Williams Fork Formation. However, Patterson et al. (2003) mainly identified large-scale, third-order sequences within the entire Williams Fork Formation and Shaak (2010) focused her study in the only the southeastern part of the basin within the lower Williams Fork Formation. Both of these sequence-stratigraphic studies were dominantly composed of subsurface data with some core and minor outcrop data. Studies in the Piceance Basin within the Williams Fork Formation tend to be purely subsurface correlations, documenting only major sequence boundaries and systems tracks which overlook the high-frequency surfaces and detailed facies

(Cumella and Scheeval, 2008; Leibovitz, 2010). Other studies which are more field work intensive however, tend to only focus on certain areas of the basin. Collins (1975) was primarily characterizing coals within the Williams Fork Formation and although his sections were more generalized, was able to correlate the Trout Creek Sandstone Member of the Iles Formation and Middle and Upper Sandstones of the lower Williams Fork Formation along the eastern margin of the basin (Appendix A). Madden (1989) was also more focused in a particular area of the basin, along the Rifle Gap to New Castle transect (Appendix A Edwards 2011). These stratigraphic profiles were very detailed and used to correlate the marine sandstone packages. None of these previous studies to date have been able to successfully correlate throughout the entire basin using sequence-stratigraphic applications within the Rollins Sandstone Member to lower Williams Fork Formation interval.

Integration of all available data (outcrop, core, well log, and seismic data) improves the quality of any correlation, especially those with complex facies changes. If any of these data are missing, it can result in a decrease in the resolution of the interpretation (Catuneanu et al., 2009). Outcrop and core data are extremely beneficial for identifying depositional environments. These data are extremely helpful when working in largely nonmarine intervals in order to recognize tidal signatures which represent maximum flooding surfaces and fluvial facies stacking patterns within nonmarine successions. Cored intervals can resolve heterogeneities at a reservoir/mesoscopic scale such as bedding, stratification styles, lithologic types, and types of bedding contacts (Slatt, 2006). Cored wells are beneficial to petroleum exploration and production as these intervals can show zones which might be covered or highly vegetated in outcrop, and which are in close proximity to or within producing fields. Oil staining is also distinct and indicative of which facies are prone to host hydrocarbon accumulations. However, cores only provide three to four inches of lateral variability of these facies. Detailed field work and observations of facies, facies stacking patterns, facies juxtaposition relationships, and depositional environments can be described and interpreted. These can then be compared with nearby well logs to discern patterns and key log characteristics that correspond to these facies and correlated regionally through the basin where well log data persists.

The goal of this study was to construct a detailed, regional sequence-stratigraphic framework through shallow marine (upper Iles Formation) to nonmarine (lower Williams Fork Formation) facies along the margins of the Piceance Basin using both outcrop and well log data. This detailed framework highlights facies distributions and associated depositional environments both stratigraphically and geographically. Identifying facies relationships and stacking patterns was essential in the correlation through the nonmarine successions and illustrate regional sedimentation trends that correspond with known Laramide-style, basement-cored structures, and reactivated Pennsylvanian/Permian trends. The focus was to answer the following questions:

(1) What was the basin-scale configuration and connection of depositional systems in the Piceance Basin?

(2) Were sedimentation patterns influenced by intra-basin structural development? If so, where is this seen in the basin?

(3) Do the regional-scale sedimentation patterns correspond with known gas fields that have better production? Does this influence or effect production?

1.1 Geological Setting

The Piceance Basin is located in northwestern Colorado, spanning the area from the Book Cliffs to the Uinta Mountains (Figure 1.3). This basin forms the distal part of an extensive, ancient foreland basin, the North American Cordilleran Foreland Basin (Figure 1.3). In northwestern Colorado, the sediments of the Upper Cretaceous Mesaverde Group were deposited in the distal part of the Cordilleran Foreland Basin. Sediment was largely sourced from the Sevier fold-thrust belt (NE-SW trending belt, west of the Piceance Basin), and transported to the east and deposited in alluvial, coastal plain, and marine settings (Johnson, 1989) (Figure 1.4).

Subduction of the Farallon Plate along the western margin of North America from the latest Jurassic to Paleocene caused the development of the Sevier fold-thrust belt, a NE-SW trending, eastward-propagating belt of "thin-skinned" deformation (Johnson, 2003; DeCelles, 2004). Modeling from Jordan (1981) showed that thrust-belt loading created flexural subsidence, forming the North American Cordilleran Foreland Basin. A vast seaway, the Western Interior Seaway, formed in the North American mid-continent roughly coincident with subduction (Figure 1.5). Liu et al., 2010 proposed that subduction-related dynamic subsidence was the main driver for this transgression and foreland basin development, yet many workers still attribute the basin to flexural subsidence as first suggested by the models of Beaumont (1981) and Jordan (1981). During the latest Cretaceous, Laramide-style, basement-cored uplifts segmented the contiguous foreland basin (i.e., Uinta and Piceance Basins were segmented by the Douglas Creek Arch). These Laramide- uplifts, or basement-cored structures, punctuated the Cordilleran Foreland Basin from the Late Cretaceous to Eocene (DeCelles, 2004) (Figure 1.3). Plate subduction modeling by Liu et al. (2010) suggests that during the Late Cretaceous, the subduction of the Shatky conjugate of the Farallon plate caused rebounding of the Colorado Plateau with 600 m of uplift. This work corresponds with DeCelles (2004), and shows uplifts beginning as early as 80 Ma ago and peaking from 70-60 Ma ago, leading to the eastward migration of the Western Interior Seaway.

Tweto (1979), Cumella and Ostby (2003), and Miller (2011) have mapped out local Pennsylvanian-Permian and Laramide structural trends in detail in the Piceance Basin. The timing of these basement-cored, Laramide-style structures has been highlighted by numerous researchers, particularly around the north-south trending Douglas Creek Arch (DCA) (Mederos et al., 2005; Bader, 2009). Previous work conducted by Johnson and Finn (1986), Mederos et al. (2005), and Bader (2009) suggest that the DCA began uplifting during the Campanian through the Late Paleocene to Early Eocene. Aschoff and Steel (2011a) show high resolution sequence stratigraphy and thinning trends from another Laramide structure in the Cordilleran Foreland Basin near the San Rafael Swell (central Utah). Their work shows evidence of uplift as early as 77 Ma in central Utah. Collectively, these studies suggest that Laramide structures may be older and have a much longer kinematic history than previously recognized. The Piceance Basin is bounded by the following Laramide structures: White River Uplift and Grand Hogback (East), the Uncompahgre and Sawatch uplifts (south), the Douglas Creek Arch (west), and the Uinta Mountains and Axial Basin Anticline (north) (Cole and Cumella,, 2003; Patterson et al., 2003) (Figure 1.6). The beds dip steeply in the east (>60°) along the Grand Hogback, whereas in the south and western part of the basin, the beds dip from 1-20° (Cole and Cumella. 2003). Structurally, the deepest part of the Williams Fork Formation ranges between 1830- 2740 m (6000-9000 ft) with formation pressures from 0.5-0.8 psi/ft. These pressures indicate an over-pressured system (Cole and Cumella, 2003).

During the Campanian and Maastrichtian times, much of this study area was occupied by the western margin of the Western Interior Seaway (WIS) (Figure 1.5). The WIS extended from Canada in the north and down to south, in the Gulf of Mexico (Johnson, 1989). The Mesaverde Group (within the late Campanian) in this study area encompasses the Iles and Williams Fork Formation. The Sevier fold-thrust belt, west of the Piceance Basin, sourced the sediment which makes up the Mesaverde Group. The Iles Formation consists of three regressive marine sandstones with intertonguing marine shales and conformably overlies the marine Mancos Shale. From oldest to youngest, the three transgressive-regressive shoreline units are: The Corcoran, Cozzette, and Rollins Sandstone Members. Aschoff (2008), Aschoff and Steel (2011a, 2011b) identified two distinct clastic wedge types within the Iles Formation and its correlative units to the west. "Wedge B" consists of the Middle Castlegate Sandstone (Ss), Sego Ss, Neslen Formation, Corcoran, and Cozzette Members while "Wedge C" consists of the Rollins Ss , Bowie Shale, and lower Williams Fork Formation. Wedge B revealed a flat-to-falling shoreline stacking pattern, highly progradational (400 km in 1.9 Ma) with both wave and tide influenced shorelines and relatively thin (< 125m). Wedge C however, showed a rising shoreline stacking pattern, with wave-dominated successions and much thicker (>400m) (Figure 1.4a) (Aschoff, 2008; Aschoff and Steel, 2011a; Aschoff and Steel; 2011b).   The shoreline of the Rollins Sandstone, also called the Trout Creek Sandstone, in the Piceance Basin has a north-northeast to south-southwest orientation (Figure 1.2) (Johnson, 1989; Johnson, 2003; Gomez-Veroiza and Steel, 2010). The Rollins Sandstone Member is a very fine- to coarse-grained sandstone and ranges from 0-200 ft, thickening to east. It has been interpreted as a regressive nearshore environment with prodradational and aggradational characteristics (Hettinger and Kirschbaum, 2003; Pranter et al, 2009).

The Williams Fork Formation ranges in thickness from 1200 ft to 5000 ft shifting from the UT-CO state line to the eastern margin of the basin. Thickness variation is thought to be attributed to combined effects from a regional erosion surface at the top of the Williams Fork Formation and subsidence caused by differences in deposition (Johnson and Roberts, 2003; Cole and Cumella, 2005).

Ammonite and radiometric dating from Gill and Hail (1975) and Cobban et al. (2006), strengthens age constraints of this stratigraphic interval especially within the marine environments in the Iles and Williams Fork formations (Figure 1.2). Marine successions in the Williams Fork Formation are predominately concentrated in the eastern part of the basin within the Bowie Shale interval which pertains to this study (the Lion Canyon Sandstone is another marine environment stratigraphically located in the “upper” Williams Fork Formation overlapping in the northeastern part of the Piceance Basin and southern Sand Wash Basin). Although Madden (1989) uses different terminology for marine sandstone units near New Castle, Colorado, the “Haas Sandstone” is still interpreted to lie stratigraphically in the Bowie Shale Member of the lower Williams Fork Formation. At the base of the “Hass Sandstone,” Madden (1989) identified the westernmost extent of the ammonite *Didymoceras cheyennense,* within the Williams Fork Formation. Compiled palynological data from Roberts and Kirschbaum (1995) reveals that during the “Campanian II” (79 Ma-72Ma) is poorly constrained within the *Aquilapollenites quadrilobus* zone (Appendix A).

The study area encompasses the Mesaverde Group outcrop belt along the margins of the Piceance Basin, and their subsurface equivalents including Delta, Garfield, Gunnison, Mesa, Pitkin, and Rio Blanco Counties, CO (Figure 1.6 and 2.7). The stratigraphic interval for this study included the Rollins Sandstone Member of the upper Iles Formation, through the lower

Williams Fork Formation was selected based on its stratigraphic proximity to marine and coastal plain environments, where sequence-stratigraphic surfaces and relationships are easier to discern in the field and more likely to be preserved than in fluvial and alluvial dominant continental successions (Figure 1.7). The units within this interval form important gas reservoirs in the Piceance Basin.

1.2 Stratigraphic Nomenclature and Previous Stratigraphic Studies

The stratigraphic nomenclature from the Uinta to Piceance Basin changes from west to east and to the north, due to changes in lithofacies which have been mapped by previous geoscientists. Collins (1975) focused on the classification of coal deposits along the eastern margin of the basin and mapped out the marine sandstones within the lower Williams Fork known as the Middle and Upper Sandstone. Johnson (1989) measured four detailed stratigraphic profiles (Rifle Gap, Lands End, Hunter Canyon, and along the White River in the north part of the basin) as well as correlated six transects through the basin. His study focused on the stratigraphic interval from Mancos, Sego and/or the base of the Iles Formation (Corcoran Sandstone Member) through the Ohio Creek Member and Wasatch formations, documenting only major regressive shifts. The cross-sections correlated by Johnson (1989) show the overall stratigraphic changes, however, skim over the detailed facies and sequence-stratigraphic interpretation within the lower Williams Fork Formation. Tyler and McMurry (1995) identified nine flooding surfaces from the top of the Cozzette Sandstone Member in the Iles to the top of the Upper Sandstone Member in the lower Williams Fork Formation. However; only three genetic depositional sequences were defined. These three genetic depositional sequences are composed of three clastic wedges from the top of Cozzette to Rollins Sandstone Members of the Iles Formation (genetic unit 1), and the Middle Sandstone (unit 2), and Upper Sandstone (unit 3) within the lower Williams Fork Formation. Tyler and McMurry (1995) recognized these three genetic units by using coal occurrences however; their study only shows a correlation in the southern part of the basin using predominately well logs with only one previously interpreted measured section (Appendix A).

Regional, sequence-stratigraphic studies by Hettinger and Kirschbaum (2002, 2003), Kirschbaum and Hettinger (2004), and Aschoff (2008), have predominately focused on stratigraphic intervals within the Mesaverde Group along the Book Cliffs transect from eastern Utah to western Colorado. These studies focused on the interval below the Williams Fork Formation, correlating detailed, sequence-stratigraphic surfaces within the Sego/Neslen Formation through the marine Iles Formation (Corcoran, Cozzette, and Rollins Sandstone

Members) along the Book Cliffs (Appendix A). However, the complexities with correlating through the nonmarine strata within the Williams Fork Formation have led to only few identified sequence-stratigraphic surfaces. Patterson et al. (2003) identified seven third-order sequences within the Mesaverde Group within the Piceance Basin. However, this does not capture the detailed facies and high-frequency flooding surfaces that are present within the lower Williams Fork Formation.

1.3 Methods

To answer the main questions posed in this study, facies and facies stacking patterns were identified in the field to identify sequence-stratigraphic surfaces. These patterns and surfaces were then extrapolated into the subsurface using a handheld spectrometer to measure ppm U, Th, K and GR response and build synthetic well log patterns. Special attention was given to open marine and tidal influence in the outcrop to identify regionally extensive flooding surfaces.This in turn helped to build the regional sequence-stratigraphic framework from outcrop to subsurface in the lower Williams Fork Formation. This method contrasts with previous attempts to correlate the Williams Fork because it emphasizes regional flooding surfaces and deemphasizes net-to-gross patterns and coal horizons. Details regarding the methodology are discussed below.

Sixteen new stratigraphic profiles were measured with a Jacob's Staff and Abbey Level at a scale of 1:250 (Appendix B). Each of these sections includes latitude and longitude data points measured with a handheld Global Positioning System (GPS) (See Appendix B). Using a Brunton compass, the strike and dip of bedding, and paleocurrent measurements (dip and dip direction) were collected. Paleocurrent measurements document the type of sedimentary structure that was measured, the exposure of structures (2D or 3D view), and a nearby strike and dip. These paleocurrent measurements were plotted using the program, StereoWin, and placed next to the corresponding drafted stratigraphic profiles and position where they were collected (Appendix B). Of these 16 new profiles, 11 include outcrop gamma ray (GR) readings measured with a scintillometer. The GR spectrometer (or scintillometer), measured Potassium, Uranium, and Thorium concentrations in the rocks. Paleocurrents were measured at a 0.5-3m (2-10ft) interval, or whenever outcrops were exceptionally well exposed. GEORADiS RS Analyst (version 0.101) was used to extract data from dataloger in the handheld spectrometer (i.e., GR dose and ppm U, Th, K), which were then graphed in excel 2010 (Appendix B). These graphs plot the stratigraphic height of each measured GR point (entered in manually) against the dose (nGy/h) to resemble a well log GR curve (Appendix B). Interpretation of facies, facies association, and stacking patterns in each stratigraphic profile was important in order to identify sequence-stratigraphic surfaces (i.e., transgressive, maximum flooding and minor flooding surfaces, and sequence boundaries).

All available outcrop and subsurface data, including one previously published outcrop section, 16 new stratigraphic profiles and 104 public well logs from the Colorado Oil and Gas Commission) were compiled using PETRA^{tm}, an integrated well database program (Appendix C). Within the PETRA^{tm} geospatial data management and mapping software, regional correlations between well data, and isopach mapping was possible. Well data (i.e., API, names, surface location and formation tops) were imported from IHS Enerdeq® into the project, whereas raster log images were downloaded and imported from the Colorado Oil and Gas Commission and then digitized in PETRA^{tm}. The datum used for this PETRA^{tm} was the North American Datum 1983 (NAD83) in US feet (ft) with Transverse Mercator as the projection. The identification of facies associations (assigned and color coded) and distinct stacking patterns in each stratigraphic profile (phase one), were then compared to nearby well log GR curves in the subsurface. By comparing facies associations, stacking patterns, sequence-stratigraphic surfaces, and outcrop GR curves to nearby subsurface GR, spontaneous potential (SP), and RES well log curves, distinct patterns were observed. These well log patterns were important in order to extend the surfaces identified in outcrop regionally into the basin and hence, aid in the construction of the regional sequence-stratigraphic framework in the Piceance.

The methodology for approaching the regional correlation along the margins of this basin began with detailed field analysis of facies and assignment of these facies to depositional environments, or facies associations. Based on the interpreted facies associations and their stacking patterns, significant surfaces (i.e., flooding surfaces and sequence boundaries) were identified. Transgressive surfaces (green) mark the first major flooding surface and a landward shift in facies (Van Wagoner, 1995). Maximum flooding surfaces (brown) were identified and marked by the most landward extent of transgression and typically showing more marine facies. Recognition of tidal signatures or influence becomes a critical feature in dominantly continental alluvial/fluvial successions because this marks the most landward extent of transgression (i.e., the maximum flooding surface) (Shanley and McCabe, 1994). However, when tidal signatures were not present, the recognition of facies stacking patterns and/or fluvial cycles indicated changes in accommodation (which could be attributed to base level changes, tectonics, and/or climate). Sequence boundaries or subaerial unconformities (red) represent a significant hiatus and mark a fall in base-level, and basinward shift in facies and (Van Wagoner, 1995). In this project, sequence boundaries were picked by more continental fluvial facies overlying more marine facies (i.e., vertically-stacked meandering fluvial facies association directly overlying (typically a sharp, scoured bounding surface) tidal or shallow marine depositional environments.

1.4 Lithofacies and Lithofacies Associations

Thirty-four lithofacies were recognized in the Rollins Sandstone Member of the Iles Formation through the lower Williams Fork Formation. Based on distinct characteristics (lithologies, grain size, biogenic features, and sedimentary structures) observed in the stratigraphic profiles of this study, these 34 facies were grouped into three tables based on different facies tracts: fluvial, marine, and tidal environment tracts (Tables 2.1, 2.2, and 2.3). These 34 facies were assigned to nine general facies associations. Following the description and interpretation of facies are the facies associations. These nine facies associations consist of some of the 34 facies which are described herein and summarized in Table 1.4.

Fluvial Tract:

Facies 1-Distal Floodplain

Description: Facies one (Table 1.2) is composed of semi-continuous, flat- based, 1.5-5 m thick, dark gray to black, carbonaceous shale and siltstones (Figure 1.8). Siltstones are horizontally-laminated or structureless locally with carbonized leaf imprints and/or other woody debris. Carbonaceous shale also contains woody debris. This facies is poorly exposed and typically forms covered intervals with a darker grey, black or dark brown color.

Interpretation: The fissile, horizontally-laminated characteristics of this facies suggest suspension deposition with siltstones being deposited during periods of low-velocity, practically stationary flows (Nichols, 1999). The high abundance of woody material in conjunction with the dark gray, or brown to black color found in this deposit also suggest a close proximity to a source of organic matter. Due to the flat-based, semi-continuous nature of these carbonaceous shale and siltstone deposits that can sometimes occur adjacent to or scoured by sharp-based, lenticular sandstone deposits, facies one is more consistent with a floodplain depositional environment (Nichols, 1999). Floodplains form from suspension deposition and are mainly composed of primarily clay- and silt-grained particles (fine-grained sand can also be deposited by suspension deposition if flow velocities are high enough). During periods of flooding, the suspended sediment leaves the confines of the channel and as it spreads out, the velocity decrease due to flow expansion, causing coarser sediments to be deposited closer to the channel (Nichols, 1999).

Facies 2- Peat Bog, Swamp, and/or Mire

Description: This facies is characterized by a semi-continuous, flat- based, 0.10-8 m thick, black, coal (Figure 1.8), which can be interbedded with shale and minor siltstone in some locations. Facies two (Table 1.2) is structureless to blocky. Depending on the location and/or nature of the coal type, coal appears blocky from cleats (natural fractures within coal). Surfaces on the cleats can be vitric (reflective). This unit typically has a very low density, high terrestrial organic matter.

Interpretation: These relatively thick, 0.3-26 ft (0.10-8 m), accumulations of coal and interebedded, organic-rich shale deposits suggests that this facies was deposited in a long-lived peat bog, swamp, and/or mire environment based on the peat to coal compaction ratios can range from 1.4:1 to 30:1, with a median ratio of 7:1 (Ryer and Langer, 1980). Using a ratio average of 10:1 for peat to coal compaction, McCabe (1987) stated that 1 mm of coal represents 4-100 years of peat accumulation in for coals with a low ash content where removed from active clastic deposition. Collins (1975) found that the Cameo-Wheeler coal zone contains predominately low ash and low sulfur content, high-volatile C bituminous to anthracite coals, and was deposited in a freshwater environment in peat-swamp depositional settings. The total organic carbon (TOC) analysis from Yurewicz et al (2003) shows average TOC values of approximately 65 wt%. The coal and shale observed in this facies were deposited in suspension which formed in a low energy environment with minor, episodic traction transport within the low flow regime that brought silt sized sediment into the freshwater bog. The thick coals are also indicative of a slowly rising base-level. The thickest coal deposits within the Cameo-Wheeler Coal zone directly overlie a wave-dominated marine shoreface environment above the Rollins Sandstone Member. Both Patterson et al. (2003) and this study mark this surface as a significant, regional hiatus within a lowstand deposit to early transgressive deposit.

Facies 3- Meandering Fluvial Channel with Counterflow Currents

Description: Facies three (Table 1.1) is a semi-continuous, irregular-based, 0.50-5 m thick, brown to tan, very fine- to fine-grained, lenticular-shaped sandstone. Sedimentary structures within these lenses of sandstone included trough cross-strata with superimposed current-ripple cross-laminations, and ancillary soft sediment deformation (SSD) and iron concretions. Current-ripple cross-laminations interbedded with siltstone and mudstone increase in abundance and were identified towards the top of facies. Lateral accretion sets were also observed in this facies (Figure 1.8).

Interpretation: Facies three shows superimposed trough cross-strata and current-ripple cross-laminations which indicate polymodal current directions or counterflow current ripples. No tidal indicators were observed in this facies therefore, bimodal current directions are interpreted as part of a fluvial channel complex. Eddies within streams and/or the many different paleocurrent directions identified in meandering fluvial systems can also show bidirectionality. Fine-grained trough cross-strata can be found in the upper part of the low flow regime while very fine-grained ripples formed in the lower part of the low flow regime. The dominant current deposited dunes, while the secondary current deposited ripples. Based on the grain size, sedimentary structures, evidence of lateral accretion sets, this is interpreted as being deposited by traction transport under meandering fluvial processes.

<u>Facies 4- Proximal to Small Chute Channel Near Floodplain</u>

Description: Facies four (Table 1.1) is characterized by a discontinuous, irregular-based, 0.03-0.10 m thin, lenticular sandstone bodies. Typically a brown to tan color with very fine-grained, quartz-rich sandstone, with current-ripple cross-laminations and thinly interbedded with discontinuous mudstone (Figure 1.8).

Interpretation: Very fine-grained, ripple cross-laminated sandstone suggests a low flow regime dominantly by traction transport processes. Interbedded mudstone suggests suspension deposition. These two processes indicated a flow which oscillated between the lower flow regime and quiescence. Facies four is typically surrounded by floodplain mudstone deposits. Chute channels can vary in size, shape, and typically have gravels concentrated at the base of the channel with thick, planar-tabular cross-strata while chute bars are composed of smaller cross-bedding (Reading, 1986). The irregular-based, ripple-laminated cross-stratified, lenticular sandstone is interpreted as a chute bar located within the floodplain and proximal to a small chute channel.

<u>Facies 5- High Energy, Main Migration Meandering Channel Pathway</u>

Description: Facies five (Table 1.2) is a discontinuous, irregular-based, 0.50-3 m thick, tan to cream color, upper very fine- to upper medium-grained sandstone. Sedimentary structures include trough and planar-tabular cross-stratified sandstones (Figure 1.8). Planar-tabular cross-strata are typically overlying the trough cross-strata. This facies typically lacks interbedded mudstone however; increase in mudstone content can vary laterally and vertically.

Interpretation: The range in grain-size from upper very fine- to upper medium-grained sandstone and cross-bedding suggests traction transport of sand within the moderate to high flow velocities within the upper part of the lower flow regime, and deposition within 2D and 3D dunes. The irregular-based nature of the base of this facies scoured into the underlying facies and is interpreted as a channel cut. The up-section change from trough cross-strata at the base to overlying planar-tabular cross-strata indicates a decrease in flow strength and/or increase in sediment supply. This facies was deposited in a unidirectional flow, and is consistent with fluvial deposition.

<u>Facies 6- High Net-to-Gross, Vertically-Stacked Amalgamated, Main Meandering Channel Belt</u>

Description: This facies (Table 1.1) is semi-continuous to discontinuous, irregular-based, with multiple thick (1 to15 m), lenticular-shaped, sandstone bodies. Facies six is a tan to brown, fine- to upper fine-grained sandstone with granule to pebble sized mudstone clasts concentrated at base. Clasts tend to be aligned in same orientation and direction as the planar-tabular and trough cross-strata. Lateral accretion sets are observed. This facies has a high net to gross sandstone ratio (Figure 1.8).

Interpretation: Fine- to upper fine-grained sandstone with granule to pebble sized outliers within trough and planar-tabular cross-strata indicate high flow strength within the lower flow regime which decreases in flow strength stratigraphically. Imbricated, coarser-grained clasts at the base of irregular-based, lenticular sandstone bodies suggest dominantly unidirectional traction transport within fluvial channels, most likely within deposited in the thalweg of the channel. The thalweg is where the maximum channel depth is located and typically corresponds with the highest velocity within the channel (Bridge and Jarvis, 1982; Reading, 1986). Higher net to gross sandstone ratios within facies six denote a main fluvial channel migration pathway. Preservation of lateral accretion sets locally observed within this facies was interpreted as a channel within a meandering fluvial system. However, these sedimentary aspects such as planar-tabular cross-strata, trough cross-strata, and granule to pebble imbricated clasts are not diagonostic for just one particular fluvial environment.

Facies 7- High Energy, Conglomerate, at the Thalweg in a Multi-Story Channel

Description: Facies seven (Table 1.2) is composed of discontinuous, irregular-based, 0.30-1.5 m thick, brown, light tan, and/or reddish color conglomerate with subangular to subrounded siltstone clasts (Figure 1.9). These clasts can range in grain size from granule to cobble and are within a fine to upper fine-grained sandstone matrix. The base of this unit has a scalloped lower bounding surface. Sedimentary structures in this facies are composed of local soft sediment deformation, massive (structureless) units, with faint normal grading.

Interpretation: Granule to cobble sized clasts with massive to normal graded beds indicates unidirectional, high flow velocities by traction transport. Normal graded beds show a decrease in clast size moving up stratigraphically, indicating a waning flow. The irregular-based, scalloped surface at the base of this unit suggests scouring and erosion at the base of a fluvial channel. This facies is typically observed at the base of facies six and is interpreted as a vertically-stacked meandering fluvial channel.

Facies 8- High Sediment Rates/High Flow Velocities in Undifferentiated Fluvial Channel

Description: Facies eight (Table 1.2) is marked by a discontinuous, irregular basal and upper contact, 0.20-1.5 m thick, reddish tan to light tan color, fine- to upper fine-grained sandstone. Horizontally-laminated strata are common observed. Locally, soft sediment deformation and high concentrations of mudstone clasts are found at base of this unit (Figure 1.9). The composition of this facies is composed of 60% quartz, 30% feldspar, and 10% chert. Iron concretions are frequently seen in this facies.

Interpretation: Horizontally-laminated fine- to upper fine-grained sandstone for facies eight suggest high flow strengths in the lower part of the upper flow regime and/or high sedimentation rates due to an increase in sediment supply. High flow velocities and horizontal beds within a discontinuous, irregular-based, lenticular sandstone unit suggest confined, unidirectional flow at the base of a fluvial channel. The high iron concretions amounts suggest that during deposition, there were most likely a lot of organic fragments from a nearby terrestrial source. These were then transported and deposited. Afterwards, iron rich waters flowed through the rock and precipitated concentrically around the organic rich fragments. The facies descriptions are generic and apply to many different fluvial channel complexes.

Facies 9-Lower Margin of Channel, Proximal to Thalweg, Multi-Story, Vertically-Stack Meandering Fluvial Channel

Description: Facies nine (Table 1.2) is delineated by a semi-continuous, irregular-based, 15 m thick, light tan to cream, fine- to medium-grained sandstone. Sedimentary structures include: massive (structureless) at the base of the unit transitioning to horizontal bedding with overlying trough cross–strata (Figure 1.9). Fining up trend shows current-ripple cross-laminations interbedded with minor mudstone above the trough cross-strata. This unit has lenticular-shaped geometries with a width of 10-20 m. Scalloped surfaces were also observed in this facies with occasional granule to pebble clasts above these surfaces.

Interpretation: Based on the grain size transition from medium- to fine-grained moving up stratigraphically, as well as shift from massive to horizontal to trough cross-strata then to ripple laminations, this facies shows an overall decrease in flow velocities and/or transition in the position of the channel. Facies nine was deposited in a unidirectional flow by traction transport. The irregular-based, lenticular-shaped sandstone bodies represent multiple small channels and scour and fill features at or near the base of these channels. This facies is typically observed within and/or at the base of facies 5 and 6. It is interpreted as being part of a vertically-stacked, meandering fluvial channel.

Facies 10-Top of Point Bar Near Channel Bank and Proximal Floodplain

Description: Facies ten (Table 1.2) is composed of a discontinuous, irregular-based, 0.30-2 m thick, reddish tan to brown, very fine- to fine-grained sandstone. Current-ripple cross-laminations with locally interlaminated mudstone (typically not preserved) are commonly observed in this facies. This facies is also characterized by high concentrations of calcite cement and shows a fining up trend overlying the top of facies 4, 6, 8, 9, 10, 14 (Figure 1.9).

Interpretation: Very fine- to fine-grained, ripple-laminated sandstone suggests unidirectional traction transport within the lower limit of the lower flow regime. The finning up trend from ripple-laminated sandstone lenses with an increase in interbedded mudstone indicates stratigraphically, a decrease in flow velocities and/or by a change in the position of the channel. Mudstone is an indication of quiescence and transition to suspension deposition. The channel migrated through time which suggests that stratigraphically, the position was closer to the floodplain. The high calcite cement is typically observed at the top of many of facies 6, 8 and 10. The fining up of this facies appears conformable and typically capping facies 4, 6, 9, and 14. Following the classic point bar model for meandering streams by Allen (1970), Miall (1992), and many others, this fining up trend with ripple cross-laminated very fine- to fine-grained sandstone deposits are found on the edge of the point bar approaching the floodplain. This leads to the interpretation that this facies can be associated within both single-story and vertically-stacked meandering channel complexes.

Facies 11- Crevasse Splay Proximal to Floodplain

Description: Facies 11 (Table 1.2) is composed of semi-continuous to discontinuous, irregular-based (locally, can appear flat-based), 0.20- 8 m thick, gray to dark gray, clay to very fine-grained sandstone. This facies has is dominated by a carbonaceous mudstone which is interbedded with massive (structureless) siltstones which can show a coarsening up into very fine-grained current-ripple cross-laminated sandstones (Figure 1.9). There is an overall in crease in the sandstone bed thickness when transitioning up section, however there still remains an overall lower net to gross sandstone ratio for this facies.

Interpretation: The carbonaceous mudstones indicate suspension deposition. The discontinuous, structureless siltstones which coarsen up to ripple-laminated sandstones suggest traction transport within the lower flow regime. Based on the structureless and coarsening up nature of the siltstones and sandstones, this facies is interpreted to have been deposited under high sedimentation rates due to flow expansion and is associated with crevasse splay deposits. Crevasse splays are commonly associated with anastomosing fluvial systems and can be found in different climates ranging from tropical-savanna to temperate-colder climates (i.e., Magdalena River in Colombia, South America, and Banff National Park rivers, Alberta Canada respectively) (Smith and Smith, 1980 and Smith, 1986). Periods of quiescence, which deposited mudstone are interpreted as part of the floodplain. These deposits can have a unidirectional and/or multi-directional (radial) component of flow. Anastomosed channels are isolated within thick floodplain and crevasse splays deposits due to aggradation and stable, vegetated banks (lacking lateral migration of channels) (Smith and Smith, 1980; Miall, 1992). However, Törnqvist (1993) documents crevasse-splay deposits can be associated with both anastomosing and meandering fluvial systems. The preservation of crevasse splays in meandering systems, although is to a lesser extent than anastomosed systems, must be aggradational for preservation of the splays (Törnqvist, 1993). Facies 11 is interpreted as part of an anastomosed fluvial complex due to the high preservation of crevasse splays.

Facies 12-Distal Floodplain with Pedogenesis

Description: This facies (Table 1.2) is classified by semi-continuous to discontinuous, moderately flat-based, 0.10-5 m thick, gray to green mudstone and siltstone. Locally, facies 12 has very fine-grained sandstone deposits with relict current-ripple cross-laminations. Paleosols development is common in this facies and tends to have a red to green patchy appearance. Root traces which taper downward, as well as small woody imprints and fragments are prevalent as well. Slickensides are also found within this facies. A blocky to nodule fracture pattern and/or weathering characteristic is also observed (Figure 1.10).

Interpretation: The structureless mudstone suggests suspension deposition while the siltstone and relict, ripple cross-laminations in very fine-grained sandstone interbeds represent the lower part of the low flow regime under traction transport by small channels in close proximity to floodplain deposits. The greenish-gray patchy coloration, blocky to nodule texture, abundance of root traces, and woody material suggests this facies underwent pedogeneis and gleysol paleosols developed (Mack et al., 1993). Root traces are especially important as they show preserved traces of plant life, and exposure to the atmosphere enabled them to grow. Pranter et al., 2007 also documented this blocky/nodule textured, mudstone and siltstone facies and they interpreted it to also be deposited in suspension and influenced by pedogenesis (during soil formation). Paleosol development within this facies represents periods of non-deposition. Depending on the maturity of the paleosols can represent a significant amount of time of subaerial exposure (Shanley and McCabe, 1994). Paleosol identification is one of the most dependable criterions of a terrestrial environment (Nichols, 1999).

Facies 13-Anastomosed, Isolated Channel

Description: Facies 13 (Table 1.2) is characterized by a semi-continuous to discontinuous, irregular-based, lens-shaped, 8-10 m thick, light tan to tan-brown color, medium- to upper medium-grained sandstone. The sedimentary structures observed in this facies are trough cross-strata which changes stratigraphically to planar-tabular cross strata towards top of the unit (Figure 1.10).

Interpretation: Based on the medium- to upper medium-grained trough and planar-tabular cross-stratified sandstones, this facies was deposited by unidirectional flow in the upper part of the low flow regime. The lenticular sandstone body is laterally discontinuous, thickens in the middle, and is commonly found adjacent to or above facies 1, 2, 11, and 12. These facies have been interpreted as crevasse splay and floodplain deposits. The medium grain size, irregular basal surface, channel geometries, upper low flow regime, and proximity to floodplain and crevasse splay facies suggest deep channel confinement of an anastomosed fluvial complex.

Facies 14-Lateral Accreting Bars within a Meandering Fluvial Channel

Description: Facies 14 (Table 1.2) is a laterally discontinuous, irregular-based, ranging from 0.50 m- 5 m thick, red to tan color, very fine- to fine-grained sandstone. This facies has sedimentary structures composed of current-ripple cross-laminations with interbedded mudstone in between sandstone lateral accretion sets. The lateral accretion sets observed in facie 14 are on average 1-2 m thin and have built out perpendicular to paleoflow direction (Figure 1.10). There is an overall fining upward pattern with increasing mudstone concentrations both stratigraphically and laterally. This facies is dominantly composed of quartz-rich grains (70-80%), however with a slight increase in lithic fragments and feldspar relative to other facies.

Interpretation: Very fine- to fine-grained sandstone with ripple cross-laminations suggest unidirectional traction transport within the lower part of the low flow regime. Moving up stratigraphically shows a fining trend with increase in mudstone content, interpreted as suspension deposition processes. The lateral accretion sets are thinner within facies 14 and are interpreted as more isolated meandering fluvial channels. The increase in mudstone deposits stratigraphically and laterally represents the transition of the channel to closer proximity of floodplain. Not all meandering rivers follow the classic point bar model of Allen (1970) as rivers can have unsteady flows and/or varied proportions of sediment grain sizes and material (Reading, 1986). This facies is interpreted as an isoloated, meandering fluvial channel with higher proportions of suspended sediment.

Marine Tract:

Facies 15-Lower Distal Shoreface

Description: Facies 15 (Table 1.3) is a continuous, flat-based, 1- 180 m thick, black to dark gray, shale with minor siltstone. This facies shows a coarsening up trend. Sedimentary structures are structureless to horizontal laminations. This facies is very carbonaceous however; no fossils or traces could be identified as this facies is typically covered. This facies occurs below the hummocky cross-strata and/or very fine-grained wave ripples with marine burrows of facies 18 and 20 as a gradational contact (Figure 1.11).

Interpretation: The thick continuous nature of this very organic-rich shale suggests a low-energy environment deposited in suspension. Although biogenic features were not observed (typically covered), this facies was sometimes interbedded with facies18 and typically observed statigraphically below facies 18, and 20 which are hummocky cross-strata and/or very fine-grained wave ripples with marine burrows. Facies 15 represents a lower energy distal shoreface marine deposit.

Facies 16- Bioturbated Foreshore

Description: Facies 16 (Table 1.3) is a continuous, moderately flat-based, 5-10 m thick, tan-light to orange-brown color, fine- to medium-grained sandstone. Sedimentary structures observed in this facies include horizontal to low angle cross-strata, with horizontal bedding observed at the base and vertical *Ophiomorpha* burrows structures typically seen at the top of the unit though in low abundance (Figure 1.11). Iron concretions can preferentially occur with *Ophiomorpha* burrows. This facies is quartz-rich and a well sorted sandstone however, a mixture of sandstone and mudstone occur near bioturbated zones.

Interpretation: Fine- to medium-grained well-sorted, quartz-rich sandstone with low angle cross-strata indicates a mature, moderate to high energy environment which is seen in wave-dominated systems. Horizontal to low angled cross-strata with fine- to medium-grained deposits are commonly observed within the foreshore and upper shoreface deposits in wave-dominated shoreline profiles (Clifton, 2006). Bidirectional(?) flow by traction transport under wave action are the main depositional processes. The low diversity of organism traces and low abundance of *Ophiomorpha* burrows indicates either a high energy (intense wave action) environment where only the opportunistic organisms thrive and/or stressed environment due to changes in salinities. *Skolithos* ichnofacies are primarily associated with relatively high levels of wave or current energy within well-sorted sandstone and are commonly found in the upper shoreface and foreshore deposits (Pemberton, 1992). Based on the low abundance of marine burrows, types of trace makers, grain size, composition, and sedimentary structures, this facies is interpreted as part of a wave-dominated foreshore to upper shoreface deposit.

Facies 17- Non-Bioturbated Upper Shoreface

Description: Facies 17 (Table 1.3) is a continuous, flat-based, 1-20 m thick, white to light tan “bleached”, fine- to medium-grained homogenous sandstone. The main sedimentary structures preserved are bidirectional trough cross-strata. There is very minor evidence of bioturbation, with few *Skolithos* trace fossil burrows observed. This facies is a clean, well-sorted sandstone composed of more than 90% quartz and less than 10% minor lithics/chert. Facies 17 also has a distinct weathering pattern that weathers round and/or can have a honeycomb-like fracture pattern. There are round iron-oxidized circles (0.4-0.6 m in diameter) present at the top of this surface locally (Figure 1.11).

Interpretation: Fine- to medium-grained, well-sorted, well rounded, quartz-rich sandstones with highly bidirectional trough cross-strata suggests moderate to high wave influenced deposits observed typically in the upper shoreface. This facies has been interpreted as deposited under bidirectional traction transport. The low to zero abundance and diversity of organisms and/or traces signifies moderate to high energies from constant waves reworking the paleoshoreface. The bleached color of this facies is due to the leaching of the overlying facies 1 and 2 down through to this facies.

<u>Facies 18-Storm Deposits in the Middle Shoreface</u>

Description: Facies 18 (Table 1.3) is a continuous, flat-based, 1- 10 m thick, tan to brown color, siltstone to very fine-grained sandstone. The main sedimentary structures are hummocky cross-strata with interbedded mudstone locally. Trace fossils from the *Cruziana* and *Skolithos* ichnofacies families, such as *Thalassinoides* (identified at the base of this unit) and *Ophiomorpha* (top of unit) respectively are some of the burrows observed in this facies (Figure 1.11).

Interpretation: Siltstone to very fine-grained hummocky cross-strata is indicative of storm-wave action within the lower shoreface of a wave-dominated system. This facies was deposited during intermixed high and low bidirectional flow energies, with the high energy lasting a short time. The siltstone grained size material was deposited in low energy traction transport and re-worked by higher energy storm-waves which deposited very fine-grained sandstone. This facies has a moderate diversity and low abundance. The transition from *Cruziana* and *Skolithos* ichnofacies stratigraphically upward (*Thalassinoides* at the base of the facies and *Ophiomorpha* at the top) suggest a change in the environmental conditions. This is most likely attributed to *Cruziana* ichnofacies tend to like moderate to low energy levels in quieter waters while *Skolithos* ichnofacies tend to be opportunists and high energy levels. This suggests a shift from low to moderate energies into higher wave energies associated with storm waves. The latter criterion has led the author to conclude this facies was deposited in the lower shoreface.

Facies 19- Chaotic, Highly Biotubated Facies within the Middle Shoreface

Description: Facies 19 (Table 1.3) is characterized by a semi-continuous to continuous, flat-based, 0.20-1 m thick, light tan to a brown, very fine- to medium-grained sandstone This structureless sandstone is highly bioturbated, however, no organisms could be identified (possibly *Thalassinoides* in Figure 1.12, however it is difficult to discern). It has a mottled and chaotic appearance, with highly heterolithic mixture of mudstone with quartz-rich sandstone (Figure 1.12).

Interpretation: Based on the high abundance and/or diversity of bioturbation, this facies is interpreted as having very suitable conditions for organisms to survive and therefore is concluded to have been deposited in a wave-dominated, middle to lower shoreface environment. Direction of flow cannot be determined in this facies from the high bioturbation, however, the process of deposition suggests both traction transport and suspension deposition were in close proximity to one another. Pemberton et al. (1992) concluded that most trace fossils are common or in more abundance in the middle through proximal offshore deposits. The medium-grained sandstone suggests that this facies is most likely deposited in the middle to lower shoreface.

Facies 20-Storm Waves and Wave Ripples within Middle to Lower Shoreface

Description: Facies 20 (Table 1.3) is a continuous, flat-based, 0.50-3 m thick, tan to gray, mudstone to very fine-grained sandstone. The clay sized particles are prone to weathering out. Wave ripples interbedded with horizontally-laminated carbonaceous shale were the main sedimentary structures identified (Figure 1.12). Hummocky cross-strata were also observed near this facies with vertical burrows. Biogenic traces represented a low diversity and low to moderate abundance. Traces included *Thalassinoides*, unknown vertical burrowing, and *Diplocraterion*.

Interpretation: Very fine-grained, symmetrical wave ripples interbedded with thin horizontally-laminated mudstone suggest bidirectional flow by dominantly traction transport and minor suspension deposition within a wave-dominated environment. Hummocky beds are interpreted as storm events which attributed to the moderate abundance of vertical burrows found locally in this facies. These sedimentary structures and vertical burrowing (*Skolithos)* trace fossils indicate a wave-dominated middle shroeface to lower shoreface environment.

Facies 21- High Diversity, High Abundance with *Inoceramus* in the Middle to Lower Shoreface

Description: Facies 21 (Table 1.3) is a semi-continuous to continuous, flat-based, 0.20-2 m thick, creamy tan to gray-brown, clay to fine-grained sandstone. This bioturbated, structureless, heterolithic sandstone and mudstone facies has an *Inoceramus* bivalve *(*from 2cm to 30 cm in size) stratified layer, typically found at the base of a bed and oriented concave down. Many traces within the *Cruziana* and *Skolithos* ichnofacies families were identified. The base of the facies consisted of *Inoceramus* bivalves, and traces *Asterosoma*, and *Asteriacites* were identified. At the top of this unit *Rhizocorrallium*, *Arenicolites*, and *Planolites* traces persisted (Figure 1.12).

Interpretation: Pemberton et al. (1992) concluded that most of the high abundance and high diversity of traces occurs within the middle to lower shoreface in wave-dominated shoreline environments. The very high diversity and high abundance of traces and fossils within this facies indicates an environment conducive for organisms to have survived and has been interpreted to have been deposited in the middle to lower shoreface in a wave-dominated shoreline. The direction of flow is difficult to determine due to low preservation of sedimentary structures from high bioturbation. However, both traction transport and suspension appear to have been the main processes based on the heterolithic nature of this facies (mudstone and sandstone intermixed). This facies was deposited in a low to moderate wave energies.

Facies 22- Interlaminated Shell Fragments within Cross-Strata in the Upper Shoreface

Description: Facies 22 (Table 1.3) is a semi-continuous to continuous, moderately flat-based, 0.10-5 m thick, tan to cream color, upper fine-grain sandstone. Trough cross-strata with some bidirectional planar-tabular cross strata are the main sedimentary structures present in this facies. Small bivalve and broken shell fragments are highly concentrated along cross-stratified surfaces near the base of this facies. No bioturbation was observed in this facies (Figure 1.13).

Interpretation: Upper fine-grained trough and planar-tabular cross-strata with interbedded shell fragments suggests nearshore marine to tidally-influenced origins within a moderate to high wave or tidal energy. This facies was deposited under bidirectional flow, traction transport. No bioturbation could represent a stressed environment from either changes in salinities, high wave action constantly reworking sediments, or an active tidally-influenced channel within the upper part of the low flow regime. Ichnofacies adaptation to their surrounding environment provides insight into the conditions at the time of deposition such as: food supply, hydrodynamic energy, salitinity, water turbidity, sedimentation rates, temperature, oxygen concentrations, and the substrate to name a few (Frey and Pemberton, 1984; Pemberton, 1992). This facies is not distinct to one particular association and could have been deposited in the upper shoreface, tidally-influenced channels, or bayhead deltas. However facies 22 has been categorized into marine influenced (Table 1.3) facies and interpreted as influenced by wave processes in the upper shoreface due to the highly broken up shell fragments aligned in cross-strata.

Facies 23-Swaley Cross-Strata in the Middle Shoreface

Description: Facies 23 (Table 1.3) is characterized by a continuous, moderate to flat-based, 0.50-5 m thick, tan to cream, upper fine- to medium-grained sandstone. Sedimentary structures include low angle cross-stratification to swaley cross stratification. Minor to no bioturbation was observed in this facies (Figure 1.13).

Interpretation: Upper fine-(swaley cross-strata) to medium (low angle cross-strata) suggests moderate to high energy along a wave dominated shoreface. This facies was deposited by bidirectional rapid traction transport and minor suspension settling influence. Swaley cross-strata indicate deposition from storm waves and are typically associated with the lower middle to lower shoreface (Clifton, 2006). Medium-grained, low angle cross-strata are more associated with the middle shoreface, which accounts for the increase in grain size. The lack of trace fossils could also be attributed to this depositional environment where moderate to high wave energy with storm influences created stressed environments for organisms to survive (Pemberton et al., 1992).

Facies 24-Low-Angled Cross-Strata with Load Casts in the Upper Shoreface

Description: This facies (Table 1.3) is a continuous, moderately scalloped to flat-based, 5 to 10 m thick, tan, well-sorted, medium-grained sandstone. Sedimentary structures observed were massive to low-angle cross-strata, with faint current-ripple cross-laminations towards the top of the unit. Unusual, unidentified horse shoe-shape load casts or possible trace fossil, which range in size (diameters ranging from 2 cm to 30 cm) are dispersed locally at the base of this facies (Figure 1.13).

Interpretation: Well-sorted, medium-grained massive to low angle cross-strata suggest deposition in a wave dominated upper shoreface to backshore environment by bidirectional, traction transport processes. The preserved load casts at the base of this facies are interpreted to be caused by erosive, scouring events or some sort of biogenic trace. The decrease in grain size and initiation of low flow regime sedimentary structures indicates decreasing wave energy stratigraphically. Overall, this facies is interpreted within the upper shore to foreshore environment

Facies 25-Hummocky Cross-Strata with Low Oxygen Burrows in the Lower Shoreface

Description: Facies 25 (Table 1.3) is a semi-continuous to continuous, flat-based, 0.20-1 m thick, white to tan, very fine- to fine-grained sandstone. It is a well sorted, low angle to hummocky cross-stratified sandstone.   *Chondrites* can be identified at the top of facies bed with many branching tunnels which do not inter-penetrate (Pemberton et al., 1992) (Figure 1.13).

Interpretation: Very fine- to fine-grained, well-sorted, low angle to hummocky cross-strata with *Chondrites* burrows suggests that this facies was deposited in a moderate wave energy environment primarily by bidirectional flow in a mixed traction transport by storm waves (rapid) and suspension (minor) processes. Experimental results from Dumas and Arnott (2006) suggest that hummocky cross-strata are generated by high oscillatory velocities and oscillatory-dominant combined flow and forms above storm wave base where aggradation rates are high in order to preserve hummocks. *Chondrites* burrows are associated with in low oxygen conditions within the lower shoreface of a wave-dominated shoreline (Pemberton et al., 1992).

Facies 26-Flood Tidal-Washover Deposit

Description: Facies 26 (Table 1.3) is a continuous, flat-based, 0.50-1.5 m thick, reddish tan to creamy white color, ranging from a very fine- to upper very fine-grained sandstone. Current-ripple cross-laminations are more pervasive, with climbing ripples and water escape structures preserved locally. *Conichnus* trace fossil, part of the *Skolithos* ichnofacies, was observed with characteristic burrows that form chevrons or a V-shape laminae in unit (Pemberton et al., 1992) (Figure 1.13).

Interpretation: Very fine- to fine-grained current-ripple cross-laminated sandstones suggests that this facies was deposited in by a unidirectional current flow (possibly bidirectional however, not preserved). Climbing-ripples are a part of the upper flow regime and represent high sedimentation rates. *Conichnus* trace fossils presents conflicting locations on where they typically reside. Pemberton et al. (1992) interpret the *Conichnus* burrow to be associated with the upper part of the lower shoreface to middle shoreface in a wave dominated environment.

However, their case study which examines the Spring Canyon Member of the Blackhawk Formation near Price, Utah, shows they only found the *Conichnus* trace within a flood tidal inlet/washover deposit. This environment is typically found in shallow marine, back barrier/lagoon environments. Climbing-ripples of this facies fit in with the flood tidal inlets and wash over deposits due to flow expansion and high sediment fall out rates. These deposits are also more likely to be preserved than ebb tidal deltas, which are located on the more basinward side of the barrier and would be reworked by waves.

<u>Tidally-Influenced Tract</u>

<u>Facies 27-Chaotic Shell Hash Deposit</u>

Description: Facies 27 (Table 1.4) is a continuous, irregular-based, 0.10-1 m thick, tan to red, clay to very fine-sandstone. This facies is characterized by a structureless, chaotic distribution of clams, gastropods, shale clasts, and wood fragments. This facies is also characterized by having local soft sediment deformation (Figure 1.14).

Interpretation: The very fine-grained, structureless, and high concentration of clams and gastropods within this sandstone suggests a more brackish water environment, with high sedimentation rates. This facies was deposited by possibly unidirectional flow (no evidence of bidirectionality, however bidirectional sedimentary structures are typically not preserved) under traction transport. Woody material suggests a proximal source to terrestrial organic material, possibly either a delta or river. This facies is interpreted to be deposited in a tidally-influenced channel within brackish to lagoon environments.

<u>Facies 28-Inclined Heterolithic Strata</u>

Description: Facies 28 (Table 1.4) is a semi-continuous to discontinuous, moderate to flat-based, 0.50- 5 m, tan to red, clay to very fine-grained sandstone. Inclined heterolithic strata dipping between 10-15 degrees can be found in this facies where organic rich mud drapes are interbedded across entire sandstone package and shows an overall fining up pattern. Internal sedimentary structures within each inclined heterolithic very fine-grained sandstone bed are composed of current-ripple cross-laminations (Figure 1.14).

Interpretation: The alternating mud draped surfaces and very fine-grained sandstone indicate transition from traction transport through some sort of channel then to suspension depositional processes of mudstone during a slack water period. This facies is interpreted to have moderate to low energies and deposited within a tidal channel or tidally-influenced environment. Inclined heterolithic strata are found within meandering tidal channels, and most abundant in the late filling of an estuary and building of the bayhead delta (Thomas et al., 1987; Boyd et al., 2006). Facies 28 sometimes occurred proximal to the burnt coal "clinker" zones within this study which destroyed many textures locally.

Facies 29-Tidal Channel

Description: Facies 29 (Table 1.4) is composed of semi-continuous to continuous, 0.20-1 m, thick, white or red, very fine- to fine-grained sandstone. It is predominantly structureless with local relict bidirectional current-ripple cross-laminations. This facies is also highly bioturbated, with *Diplocriterion* traces still preserved (Figure 1.14).

Interpretation: Very fine- to fine-grained, structureless and bidirectional ripples with high bioturbation suggests this facies was deposited in a tidally-influenced environment under moderate energies which were suitable conditions for organisms to survive. This facies was deposited by traction transport. Suspension deposition is probable, however, high bioturbation mixed sandstone and mudstone together which destroyed most sedimentary structures and no mud drapes could be identified. *Diplocriterion* is a trace fossil associated with the *Skolithos* ichnofacies which can be found in middle shoreface environments as well as sandy tidal flats and estuarine channel deposits (Pemberton et al., 1992). Facies 27 is indicative of a flooding surface or transgression, as this facies overlies more fluvial facies (1, 4, 10, 12, and 14). This facies records deposition by tidal influence within a channel.

Facies 30-Bayhead Delta within a Wave-Dominated Estuary

Description: Facies 30 (Table 1.4) is semi-continuous to continuous, flat-based, 1-5 m thick, with alternating tan and gray, ranging from clay to very fine-grained sandstone. This facies consists of flaser, wavy, and/or lenticular bedded (bidirectional ripple cross-laminated) with interbedded mud drapes (Figure 1.14). An increase in ripple cross-laminated sandstone shows only thin mud drapes typically in the ripple troughs and a more connected appearance between the ripple cross-laminated sandstones. An increase in mud drapes and/or mudstone can show discontinuous and isolated ripple cross-laminated sandstone lenses and a fining upward trend, however, coarsening up trends were identified towards the top of this unit as well.

Interpretation: Deposition of clay to very fine-grained ripple cross-laminated, flaser, wavy, and/or lenticular bedded sandstones and mud drapes suggests fluctuating hydraulic conditions. Very fine-grained ripples are part of the lower part of the low flow regime and are deposited under traction transport processes. Mud and clay size particles are deposited by suspension settling during periods of quiescence or slack-water conditions. The bidirectional currents and sedimentary structures (flaser, wavy, lenticular bedding) suggest tidal influence, leading to the interpretation of this facies being associated with a tidal environment. Bayhead deltas can also have tidal influences toward the clinoform toe and show a coarsening up trend (Aschoff, 2009) due to the prograding bayhead delta into the central basin within a wave dominated estuary (Boyd et al., 2006).

<u>Facies 31-Tidal Bundle Proximal to Tidal Floodplain</u>

Description: Facies 31 (Table 1.4) is a semi-continuous to discontinuous, 0.10-0.50 m thick, white and/or sometimes tan to brown color, upper fine-grained sandstone. The sedimentary structures identified were sigmoidal cross-strata which were separated by very thin mud drapes (typically eroded out) and systematic changes in lamina thickness. The sandstone in this facies was very quartz-rich sandstone (Figure 1.15).

Interpretation: Sigmoidal bedding of upper fine-grained sandstone with interbedded mud drapes and systematic trends in lamina thickness (i.e., bundling) suggests deposition by tidal currents. Tidal bundles represent spring-neap tide cyclicity and the deposition of one tidal cycle, which is one of the hallmarks of tidal environments (Dalrymple, 1992; Dalrymple and Choi, 2007). The upper fine-grained sandstone suggests traction transport with mud drapes indicating slack-water or quiescence during suspension settling.

<u>Facies 32-Undifferentiated Estuarine Environment (Distortred from Proximity to Buring Coals)</u>

Description: Facies 32 (Table 1.4) is a continuous, flat-based, typically multi-colored brown to orange (however, can also appear yellow, red, gray, and black), ranging from a clay to very fine-grained sandstone. Sedimentary structures in this facies include structureless due to the clinker (burnt coal), mudstone, and siltstones with interbedded sandstones. Although much of the sedimentary structures of this facies are distorted, coarsening up trends and horizontal bedding to possible lenticular sandstone bodies (10-20 cm in thickness) separated by thin (1-5 cm) mudstone layer. Also observed in the field were high abundance woody debris, leaf and pine cone imprints, and slickensides and root traces (found in high concentrations locally). *Teredolites* (elongate cylindrical burrows perpendicular to a wood substrate) burrows were preserved and found within contorted to lenticular shaped sandstone body (Figure 1.15).

Interpretation: Distortion of features due to the burning of coal deposits make it difficult to distinguish sedimentary structures and features in order to assign a depositional environment. However, the relict horizontal bedding and lenticular sandstone bodies with mud draped surfaces suggest fluctuating hydraulic conditions combining traction transport with suspension deposition or a tidally-influenced environment. Woody fragments and debris, leaf and pine cone imprints suggest a proximal source to terrestrial organic material. Slickensides are common morphological features identified in vertisol paleosols and are indicative of expanding and sweeling clays (Mack et al., 1993). Root traces are commonly found in paleosols in this facies and represent a pause in deposition for soil development. This would indicate a closer proximity to more terrestrial, edge of estuary or non-active tidal channels, possibly closer to more fluvial influence within the floodplain. The trace fossils observed in this facies provides further evidence into the insight of this depositional environment. Moran et al. (2009) distinguishes the *Asthenopodichnium Xylobiotum* trace is differentiated from *Teredolites* by its parallel orientation of the trace along the elongated wood surface, scoop-like shaped tube, and semi-circle boring. *Teredolites* is characterized by perpendicular orientation of burrows to a wood substrate, clavate or club-like shape, and more circular cross-section through the burrow. *Asthenopodichnium Xylobiotum* is associated with freshwater fluvial deposits while *Teredolites* is associated with estuarine or nearshore marine deposits. Therefore, this facies is interpreted as a tidally-influenced, estuarine bayhead delta deposit.

<u>Facies 33-Floodplain Proximal to Tidal Environment</u>

Description: Facies 33 (Table 1.4) is a semi-continuous, flat-based, 0.20- 10 m thick, alternating greenish gray and orange, ranging from clay to upper very fine-grained sandstone. Sedimentary structures are predominantly structureless siltstones and shales and locally interbedded with thin (less than 5 cm in thickness) upper very fine-grain horizontally laminated sandstone. Minor bioturbation (possibly *Planolites)* was found on the top of bedding surfaces (Figure 1.15). Minor shell fragments (small bivalves) and root traces were also identified in this facies. This facies had a high gamma ray response.

Interpretation: This facies dominantly consists of clay to siltstone-grained deposits and is interpreted to mainly have been deposited by suspension processes. The horizontally-laminated very fine-grained sandstone could indicate either the lower part of an upper flow regime or high sedimentation fall out rates. Since there is predominately shale and siltstones within this facies and the thin horizontally laminated sandstones are not lenticular bodies with scoured bases, it is interpreted that these are from high sedimentation fall out rates, associated with crevasse splays or minor flooding events and proximal to the floodplain. This facies occurs near or laterally next to facies 28 (inclined heterolithic strata). *Planolites* can resemble the trace *Palaeophycus* however is differentiated by its unlined walls and burrow fill which has a different texture than the rock it's burrowing through (Pemberton et al, 1992). The trace *Planolites* is not a very distinct burrow for recognizing depositional environments due to its simplistic morphology. This trace can be found in fluvial to deep sea settings. The main criterion that places this facies within tidally-influenced is mainly on the proximity to other tidally-influenced facies (Facies 28, 29, 30, 31, 32, and 34). This facies is interpreted to be part of the tidal floodplain.

Facies 34-Rhythmic Climbing-Ripple Cross-Lamination within tidal channels

Description: Facies 34 (Table 1.4) is a semi-continuous, moderately flat-based, 0.10- 1 m thick, white to gray, fine- to upper fine-grained sandstone. This facies is characterized by climbing ripples with interbedded mud drapes, and lenticular sandstone bodies, with minor to no bioturbation observed (Figure 1.15).

Interpretation: This facies of fine- to upper fine-grained sandstone with climbing ripples suggests a unidirectional flow (possibly bidirectional, though not preserved)) where traction transport and minor suspension settling processes dominate. Climbing ripple cross-laminations form during a waning flow where high bedload transportation rates are combined with high suspension loads (Jopling and Walker, 1968; Choi, 2010). Climbing ripples which form in tidally-influenced environments differ from other environments due to the presence of mud drapes. "Rhythmic climbing-ripple cross-laminations (RCRL)" documented in previous studies are diagnostic indicators of tidal channels within the fluvial to estuarine settings (Tessier, 1993; Choi, 2010). The lack of trace fossils indicates a stressed environment either from high sedimentation rates, and/or changes in salinities. The lenticular-shaped, fine- to upper-fine-grained, RCRL sandstone is interpreted to be associated with tidal channels within the tide-influenced-fluvial to estuarine environment.

Facies Associations

Facies Association A: Multi-Story, Vertically-Stacked, Meandering Fluvial

Description: Facies association A (Table 1.5) is a semi- continuous, irregular-based unit which can range in thickness from 1 to > 20 m. This association is typically a tan to light gray color, with occasionally a red to brown color capping the unit. Grain sizes range from very fine-grained sandstone to a conglomerate. The base of lenticular-shaped, scalloped bodies is a conglomerate with occasionally aligned or imbricated shale and siltstone clasts ranging from granule to cobble size within a very fine- to fine-grained matrix. Above this facies is characterized by horizontally-bedded, trough and planar-tabular cross-strata with thin (3-30 cm) fine-grained current-ripple cross-laminated sandstone interbedded. Structureless and rooted mudstones are present locally. There can be a fining up trend; however, a blocky stacking pattern is more prominent. This association has a high net to gross ratio due to large amalgamated and vertically-stacked channels. Lateral accretion sets are characterized with cross trough and planar-tabular strata at the base and fine into more ripple cross-laminated sandstones toward the top (Figure 1.16A). This association is composed of facies 4, 5, 6, 7, 8, 9, 10, 12 (Table 1.2).

Interpretation: Very fine-grained to cobble size clasts and horizontal bedded, trough and planar-tabular cross-stratification suggests high flow velocities to transport such large clasts and produce sedimentary structures in the upper part of the low flow regime (cross-strata) and lower part of the upper flow regime (horizontal bedding). This facies association was deposited by unidirectional flow under traction transport. The highly cannibalized lenticular sandstone bodies which tend to stack vertically, suggests highly amalgamated channels. There is minor siltstone and mudstone deposits with indicates lack of suspension deposition and hence minor floodplain deposits. Shanley and McCabe (1993 and 1994) discuss similar multi-story, amalgamated fluvial deposits with high sandstone net to gross due to cannibalization of floodplain deposits from Cretaceous strata in southern Utah (Kaiparowits Plateau). The fluvial deposits they identified were interpreted to be associated with fall in base level or decrease in accommodation. Lateral accretion sets are commonly associated with meandering fluvial systems. This association is interpreted as a multi-story, vertically-stacked, meandering fluvial channel complex.

Facies Association B: Isolated, Single-Story, Meandering Fluvial

Description: Facies association B (Table 1.5B) is overall composed of a discontinuous, irregular-based, 1 to 10 m thick, tan/reddish tan to light gray, lenticular-shaped very fine- to fine-grained sandstone. The sedimentary structures observed show trough cross-stratification with superimposed current-ripple cross-laminations which locally contains soft sediment deformation including dish-pillar structures (Figure 1.16B). Cross-stratification typically occurs at the base of this association with ripple cross-laminated sandstones at the top of the unit. This association has an overall fining up trend. Lateral accretion sets are preserved and located perpendicular to flow; however, there is typically lower net to gross sandstone ratio. Facies association B is composed of facies 1, 2, 3, 4, 5, 8, 10, 12, and 14 (Table 1.2).

Interpretation: Discontinuous, scalloped to irregular-based lenticular sandstone bodies suggest scouring due to confined, unidirectional channel flow. Very fine- to fine-grained cross-strata and ripple laminated sandstones were deposited under traction transport and show a transition in flow velocities from the upper part of the low flow regime to the lower part of the low flow regime. This indicates a decrease in flow strength and attributes to the overall fining up trend. Based on the orientation of the lateral accretion sets, these are interpreted as point bar deposits which are dominantly associated with lateral migration in meandering fluvial environments (Miall, 1992). This facies association has been interpreted as a meandering fluvial channel, with high floodplain/overbank deposits, and/or small chute/single story channels which are more isolated within fluvial floodplain deposits. Pranter et al. (2009) also documented single-story, sinuous-channel systems within floodplain deposits in the lower Williams Fork near Coal Canyon, north of Palisade, CO.

<u>Facies Association C: Anastomosed Fluvial Complex</u>

Description: Facies association C (Table 1.5) is characterized by a discontinuous to semi-continuous, irregular-based, a large (4-8 m thick) lenticular-shaped (typically scalloped surface at the base) fine- to medium-grained sandstone. Typically has thick (1-15 m) interbedded clay and siltstone to very fine grained sandstone packages. These clay and siltstones typically are highly concentrated with root traces/woody debris and are thin (5-30 cm) and laterally discontinuous. The very fine grained sandstones are composed of either current-ripple laminations and/or are structureless (10-40 cm) and typically show a coarsening up pattern. The top of this facies typically caps this unit with a discontinuous, thick, lenticular very fine to medium grained sandstone with planar-tabular cross strata. The base of this sandstone body is scalloped and has a high clay clast concentration and woody fragments (Figure 1.16C). Facies association C is composed of facies 1, 2, 4, 6, 8, 11, 12, and 13 (Table 1.2).

Interpretation: The thick discontinuous lenticular sandstones were deposited by traction transport under unidirectional flow and are interpreted as anastomosed channels. The high siltstone and mudstone concentration suggests suspension deposition within a fluvial floodplain. The coarsening up, discontinuous, very-fine structureless sandstone deposits suggest high sedimentation rates, which could be indicative of flow expansion and high sediment fall out rates which suggests crevasse splays. Root traces and paleosol development suggests a terrestrial source and non-deposition. High root traces could be indicative of highly vegetated floodplain deposits. This has been interpreted as an anastomosing fluvial channel complex, based on the high preservation of crevasse splay deposits within thick floodplain deposits (Miall, 1992). High root trace concentrations indicate vegetated, stable banks which confine the channel in a relatively stable position (in contrast to meandering and braided systems). Holocene deposits from the Rhine-Meuse Delta show that the two main controlling factors which lead to the development of anastomosed fluvial complexes are bank stability (clay and/or organic-rich beds >3-4 m thick) to inhibit lateral channel migration and a rapid rise in base level causing aggradation (Törnqvist, 1993). Anastomosed channels tend to have thicker heights than channel widths. The width to channel depth ratio was not measured, however, these channels tend to be deeper in the center than the channels identified in facies associations A and B.

<u>Facies Association D: Undifferentiated Floodplain: Coastal Plain and/or Fluvial Floodplain</u>

Description: Facies association D (Table 1.5) is a semi-continuous, flat-based, organic-rich, 0.5-20 m thick, black, dark gray, to greenish-grey shale, mudstones, and siltstones. It commonly is structureless and occasionally horizontally laminated. The carbonaceous shale and mudstone can be locally interbedded with thin coals (0.10-1 m). Root traces, woody/plant material and paleosols are commonly found in this facies association (Figure 1.6D). Facies association D is composed of facies 1, 2, 11, and 12 (Table 1.2).

Interpretation: The high concentration of shale and mudstone with horizontal laminations suggests dominantly suspension deposition. Siltstones deposited under suspension and low-velocity flows represent minor flooding episodes. Coal deposits indicate that during this stratigraphic interval, high peat and terrestrial organic matter accumulated within swamps and/or mires. Pranter et al. (2007) also identified a nodule siltstone facies within the Williams Fork Formation and interpreted the dominant processes to be suspension deposition and pedogenesis. Facies 12 of this study is resembles the nodule siltstone facies identified by Pranter et al. (2007). The nodule to blocky, greenish-gray color of paleosols within facies association D are comparable to a gleysol, which develop in regions of waterlogged, highly fluctuating water tables under low redox conditions (Mack et al., 1993). This facies association is interpreted as coastal plain, fluvial floodplain and peat bog/swamp environments.

Facies Association E: Tidally-Influenced Channels within Estuary or Deltaic Environment

Description: Facies association E (Table 1.5) is characterized as a semi-continuous, predominantly flat-based with locally irregular based beds, 1-50 m, which can be red, tan, or white in color, and very fine-fine grained sandstone in size. This facies has flaser, wavy, lenticular bedding with mud drapes and few bidirectional current-ripples preserved locally. Other sedimentary structures include structureless beds with high bioturbation, sigmoidal cross-beds, and rhythmic climbing ripple cross-laminations which are preserved locally. Lenticular sandstone bodies with trace fossils and inclined heterolithic strata were also observed in outcrop. There is a variable range in abundance and diversity of clams, gastropods. Woody debris and leaf imprints are also preserved locally. *Cruziana* (*Thalassinoides*) and *Skolithos* ichnofacies (*Diplocriterion*) are traces identified in this study area (Figure 1.17E). Facies association E is composed of facies 1, 22, 27, 28, 29, 30, 31, 33, and 34 (Table 1.2, 2.2, and 2.3).

Interpretation: Flaser, wavy, and lenticular bedding with mud drapes and bidirectional current-ripples suggests a tidally-influenced environment. Rhythmic climbing ripples and inclined heterolithic strata are indicative of tidal channels within the fluvial to estuarine transition (Tessier, 1993; Choi, 2010). This facies association is not complete flat-based due to some lenticular sandstone bodies, which are interpreted as slight higher energy tidal channels. Woody material and leaf imprints suggest a proximal source to terrestrial organic matter. Sigmoidal beds identified represent spring-neap cyclicity or tidal bundles, which are diagnostic for tidal influence (Dalrymple, 1992; Dalrymple and Choi, 2007). Facies association E is interpreted as tidally-influenced channels in an estuary or deltaic environment which occurred near swamps, protected to unprotected lagoons with wash-over deposits, and/or some type of stressed environment due to varied salinities.

Facies Association F: Estuarine, Tide-Influenced Bayhead Delta

Description: Facies association F (Table 1.5) is characterized by a semi-continuous, flat-based, 5-25 m thick, tannish white alternating with dark gray to black, very fine- to fine-grained sandstone. The sedimentary structures identified within this association are lenticular, wavy, flaser bedding (bidirectional current-ripples preserved occasionally)with higher presence of interbedded mud drapes typically observed at the base and shows an overall coarsening upward pattern with a sharp top (Figure 1.17F). Traces within the *Skolithos* and *Cruziana* ichnofacies family are preserved locally. *Teredolites* trace fossils were also identified. Facies association F is composed of facies 22, 23, 30, 31, and 32 (Table 1.3 and 2.3).

Interpretation: The flaser, wavy and lenticular bedding with bidirectional ripples and mud drapes suggests a tidally-influenced environment. However, the coarsening up trend with sharp tops, tidal bedding with mud drapes, and high mudstone concentrations at the base is indicative and interpreted as a bayhead delta within an estuarine environment. These features identifited represent some of the criterion used to recognize bayhead deltas in outcrop (Aschoff, 2009). *Teredolites* trace fossils have been identified in Campanian age strata in northern UT and western CO within brackish, high mud drape concentrations, and the fluvial-tidal transition (Steel et al., in press). Upper zones of a bayhead delta, documented in Coal Canyon, UT, show very fine-grained sandstones with climbing-ripples and planar cross- strata with interbedded mudstones (Steel et al., in press). This facies is interpreted as a bayhead delta, within an estuarine environment with some tidal influence.

Facies Association G: Upper Shoreface to Foreshore

Description: Facies association G (Table 1.5) is a continuous, flat based, 3-40 m thick, light tan to white, quartz-rich, well-sorted, fine to medium-grained sandstone. Horizontally laminated and bidirectional planar-tabular cross-strata are predominately the main sedimentary structures persevered, with load cast observed locally. Locally, *Inoceramus* bivalves can be found at base of this deposit with minor *Ophiomorphia* and vertical burrows (Figure 1.17G). Facies association G is composed of facies 16, 17, 22, and 24 (Table 1.3).

Interpretation: The well-sorted, fine- to medium-grained, bidirectional planar-tabular cross-strata signify an upper shoreface deposit under wave dominated processes. Horizontally laminated fine- to medium-grained sandstones are typically associated with the foreshore (Clifton, 2006). Minor to no vertical burrows and *Ophiomorpha* tracefossils are indicative of the high wave energy, as these burrows are opportunists and sparse in the upper shoreface environment (Pemberton et al., 1992). This facies association is interpreted as an upper shoreface to foreshore wave-dominated environment and is stratigraphically above facies associations I and H. This shows the continued coarsening up trend which corresponds with a prograding shoreface environment.

Facies Association H: Middle to Lower Shoreface

Description: Facies association H (Table 1.5) is composed of a continuous, flat-based, 2-15 m, light tan-brown, very fine sandstone. The main sedimentary structures observed in this association are hummocky cross stratification (HCS), low angle to swaley cross stratification (SCS) (slightly coarser, fine grained sandstone), structureless (from high biogenic activity), and horizontally laminated shale (Figure 1.17H). There is also pervasive bioturbation commonly within the *Skolithos* and *Cruziana* ichnofacies. Trace makers include *Ophiamorpha,* Thalassinoides, *Rhizocorrallium, Arenicolites, Planolites*, *Asterosoma* and *Asteriacites* burrows. *Inoceramus* bivalves are also clustered typically at the base of units and concave down. Facies association H includes facies 18, 19, 20, 21, 23, 25, and 26 (Table 1.3).

Interpretation: Based on the sedimentary structures (hummocky and swaley cross-strata interbedded with horizontally-laminated carbonaceous shale) and distinct biogenic trace fossils (*Ophiamorpha*, Thalassinoides, *Rhizocorrallium*, *Arenicolites, Planolites*, *Asterosoma* and *Asteriacites*) and *Inoceramus* bivalves, facies association H has been interpreted as middle to lower shoreface. This facies is found stratigraphically above facies association I, which continues with the coarsening up trend of a wave-dominated shoreface.

Facies Association I: Lower Shoreface to Offshore

Description: Facies association I (Table 1.5) is a continuous, flat based, 1-180 m, black to dark gray, organic-rich shale with interbedded with siltstone and very fine-grained sandstone. Sedimentary structures include horizontally-laminated, hummocky cross-strata, and symmetrical wave ripple cross-laminated sandstone. Biogenic features include *Thalassinoides*, *Ophiomorpha*, and facies with high, undistinguishable burrows due to intense bioturbation (Figure 1.17I). This facies association is made up of facies 15, 18, and 19 (Table 1.3).

Interpretation: This dark to medium gray facies with horizontally laminated, carbonaceous shale is indicative of low energy suspension deposition. Hummocky cross-strata and wave ripples suggest traction transport by storm wave deposits (very fine-grained) and oscillatory waves respectively. *Thalassinoides* is within the *Cruziana* ichnofacies and is associated with lower shoreface to offshore environments, however can also be found in brackish water settings (Pemberton et al., 1992). *Ophiomorpha*, within the *Skolithos* ichnofacies, is associated with brackish water deposits; however this trace is also an opportunistic trace fossil, which has also been identified in storm deposits within the lower shoreface (Pemberton et al., 1992). The proximity of these facies to each other along with biogenic traces and sedimentary structures lead to the interpretation of offshore marine to distal lower shoreface.

2.5 Facies Stacking Patterns, Accommodation Cycles, and Systems Tracts

As defined by Mitchum (1977) and Van Wagoner (1995), a sequence is "a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Van Wagoner, 1995, p. xix)." Parasequences are conformable successions and composed of genetically related beds that are bounded by flooding surfaces or their correlative surfaces, whereas parasequence sets are successions of genetically related parasequences which form unique stacking patterns and are bounded by major flooding surfaces and their correlative surfaces (Van Wagoner, 1995). These parasequences and parasequence sets, as defined by Van Wagoner (1995), are the main building blocks of a sequence and are much easier to identify in marine settings than in nonmarine depositional environments. Therefore, facies stacking patterns caused by base-level changes in fluvial successions is one of the main tools utilized to recognize fluvial cyclicity (Catuneanu, 2006).

Stratigraphic base level is an undulating equilibrium surface, fluctuating due to tectonic subsidence, eustasy, sediment supply, and discharge which intersects the earth's surface and where they intersect the surface represents erosion or low accommodation (Shanley and McCabe, 1994). Base-level changes affect accommodation (a dynamic volume of space made available for sediment accumulation where preservation occurs below the base level (Jervey, 1988)). In coastal plain and terrestrial environments, a rise in base level indicates an increase in accommodation whereas as a fall in base level represents a decrease in accommodation. However, the interplay between sediment supply and accommodation can lead to different stratal stacking patterns such as retrodradation, aggradation, progradation, sediment bypass and regional incision (Shaney and McCabe, 1994).

Marine to non-marine cycles were defined in this study in order to correlate systematic, temporal patterns in accommodation. The cycles each show a general up-section decrease in accommodation, much like a marine parasequence would. The fluvial cycles identified in this study consist of five main cycle types: tidal/coastal plain to single-story meandering fluvial (Cycle A), tidal coastal plain to vertically-stacked meandering fluvial (Cycle B), single-story meandering with undifferentiated floodplain to vertically-stacked meandering fluvial (Cycle C), tidal/coastal plain to anastomosed fluvial (Cycle D), and anastomosed to meandering fluvial with undifferentiated floodplain deposits (Cycle E). Each of these depositional environment cycles will be described below and can be found in Table 1.6.

Cycle A: Tidal/Coastal Plain to Single-Story Meandering Fluvial

Cycle A transitions upward from a tidally-influenced coastal plain environment to single-story meandering fluvial with undifferentiated flood plain deposits. This interval ranges from 15-90m (50-300ft) in thickness. Tidally-influenced facies, especially when surrounded by fully fluvial successions indicates a maximum flooding surface, which indicates a rise in the relative base level. The high concentration of mud in the undifferentiated floodplain and single-story meandering fluvial interval indicates relatively high accommodation.

Cycle B: Tidal/Coastal Plain to Vertically-Stacked Meandering Fluvial with Undifferentiated Floodplain

Cycle B consists of tidally-influenced coastal plain environments with an overlying, sharp transition into the vertically-stacked meandering fluvial facies association. This cycle can range in thickness from 9-30m (30-100 ft). Tidal facies and undifferentiated mud within this cycle mark an increase in base level and indicate more accommodation which then sharply changes to highly concentrated, vertically-stacked and amalgamated channel sandstone bodies. The transition to highly concentrated sandstone bodies indicates a fall in base level and decreasing accommodation.

Cycle C: Single-Story Meandering Fluvial with Undifferentiated Floodplain to Vertically-Stacked Meandering Fluvial

Fluvial cycle C has single-story meandering fluvial and undifferentiated floodplain with overlying vertically-stacked meandering fluvial deposits. This cycle ranges in thickness from 23-76m (75-250 ft). The single-story meandering fluvial channel and undifferentiated floodplain complex has a high concentration of mud and isolated sandstone channel bodies typically with lateral accretion sets preserved. The vertically-stacked meandering fluvial deposits above represent low accommodation and/or decrease in the base level, causing incision into the strata below. This shift in facies typically represents a sequence boundary.

Cycle D: Tidal/Coastal Plain to Anastomosed Fluvial

Cycle D is represented by tidal/coastal plain facies which transitions to an anastomosed fluvial complex. This cycle ranges in thickness from 15-30m (50-100ft). Tidal and coastal plain facies dominate the lower part of the cycle (where coals, undifferentiated floodplain muds, and tidal influenced facies dominate). The upper portion of the cycle is represented by more anastomosed fluvial deposits (i.e., deep, isolated channels and/or high proportion of crevasse splay deposits). This slight change in deposits stratigraphically indicates a slight drop in base level and decrease in accommodation.

Cycle E: Anastomosed to Single-Story Meandering Fluvial with Undifferentiated Floodplain

This cycle marks a shift from anastomosed fluvial deposits to single-story meandering fluvial with undifferentiated floodplain deposits and ranges from 15-60 m (50-200ft). The onset of more meandering fluvial deposits (more preservation of lateral accretions) overlying an anastomosed fluvial channel complex (characterized by a high preservation of crevasse splay deposits) indicates a slight decrease in accommodation.

The stacking patterns of these fluvial cycles (Table 1.6) show an overall decreasing accommodation moving up stratigraphically from the Rollins Sandstone Member through the lower Williams Fork Formation (Figure 1.18). The explanation of these accommodation cycles and type-logs are shown in Figure 1.19. When compared to well logs, these facies associations and stacking patterns tend to also change geographically when shifting from the eastern to western part of the basin. There are especially interesting changes in the stacking patterns near the Hunter Canyon area as well as near other known structures in the basin such as the Douglas Creek Arch (DCA), and the Uncompahgre and Uinta Uplifts. Directly above or in close proximity to these structures, the facies associations and stacking patterns are characterized by multi-story vertically-stacked meandering fluvial complexes and single-story meandering fluvial systems. Just off of or away from the structure however, shows fluvial cycle D (anastomosed fluvial complexes). These changes in the fluvial styles and types provide insight into timing of structures within the basin. Holbrook and Schumm (1999) discuss how tectonic deformation can affect depositional systems surrounding them (i.e., deflection of fluvial systems, changes in the fluvial styles and bed load) and how these responses can be recognized in ancient settings. For example, tectonic warping can change the gradient profile of the stream, which affects the flow velocities as well as the fluvial types. Where there is an uplift or steeper gradient, channels will tend to erode more. However, depending on the rate of growth of that particular structure, rivers could be deflected around it. Uplifting zones can also lower the stream gradient profile in backtilted areas, causing a relative base-level rise and aggradation (i.e., anastomosed fluvial complexes are associated with a relative rise in base level and associated with aggradation).

Marine stacking patterns or parasequences are well understood and were much easier to identify in this study. Marine parasequences tend to show a coarsening up, shallowing-up succession. These facies stacking patterns (moving stratigraphically up) follow a typical wave-dominated shoreface pattern: distal lower shoreface shales, overlain by hummocky-swaley cross-stratified storm deposits with lower shoreface to middle shoreface biogenic traces, which then coarsens up to horizontal, trough, and planar-tabular cross-strata within the upper shoreface to foreshore. Marine parasequences are easier to identify in the eastern part of the basin as you move closer to the Western Interior Seaway.

2.6 Key Surfaces

Previous work from Collins (1975), Tweto (1979), Hettinger and Kirschbaum (2002), and Aschoff (2008) helped with stratigraphically locating in outcrop the top of the Rollins within the Iles Formation through lower Williams Fork Formation interval. Due to complex facies transition from marine to marginal and nonmarine strata, previous studies tend to generalize the entire formation into alluvial/coastal plain environments and miss detailed facies, facies stacking patterns, and key stratigraphic surfaces (sequence boundaries, and flooding surfaces). The sequence-stratigraphic framework presented here focuses on the outcrop to identify key cycles and surfaces, then extends the outcrop framework into the subsurface.

Utilizing the lithofacies, lithofacies associations, and their corresponding stacking patterns (observed in stratigraphic profiles), key sequence-stratigraphic surfaces were picked (i.e., sequence boundaries, transgressive surfaces, minor flooding surfaces, and maximum flooding surfaces). Picking key stratigraphic surfaces in the subsurface initiated with downloading formation top picks (Top Rollins, Top Cozzette, Top Cameo, Top Mesaverde, Top Ohio Creek, and Top Trout Creek) from IHS Enerdeq® for each well log used (Appendix C). By combining the formation top picks from IHS Enerdeq® with previously published literature of formation tops picks from Tyler and McMurry (1995), Hettinger and Kirschbaum (2002), Cole and Cumella (2003), Patterson et al. (2003), and Cumella and Scheevel (2008) as well as this authors interpretation, the formation tops were picked for the data points throughout the entire basin. Once the stratigraphic location for the formation tops (top Rollins Sandstone, top Cameo, Middle Sandstone, and Upper Sandstone) were picked for each well and stratigraphic profile, the sequence-stratigraphic surfaces were then correlated from the stratigraphic profile to the nearest well log based on criterion illustrated in Table 1.7. After these surfaces were picked in the closest wells, they were correlated to other nearby wells, and gradually extended into the basin (focusing along the margins using approximately one well per township) while following the rules of sequence stratigraphy (Van Wagoner et al., 1990; Shanley and McCabe, 1994; Catuneanu et al., 2009 and others). Sequence stratigraphy focuses on facies, geospatial characteristics and distribution of strata, and identifying key surfaces within a chronostratigraphic context. The basic concept consist of understanding facies, stratal stacking patterns, and spatial relationships in order to interpret depostional systems, sequence-stratigraphic surfaces, systems tracts and sequences (Van Wagoner et al., 1990; Catuneanu et al., 2009).

Sequence boundaries mark a basinward shift in facies and surface of erosion or non-deposition and can be represented in outcrop or well-log data by: erosional truncation and well developed paleosols and rooted-horizons, onlapping relationships of overlying strata, and the identification of vertical facies stacking patterns representing non-Waltherian, basinward shifts in facies (Van Wagoner et al., 1990). Flooding surfaces are represented by a landward shift in facies and can either be trangsressive surfaces (the first onset of a landward shift in facies, indicating base-level rise) or maximum flooding surfaces (forming during base-level rise and as the most landward extent of facies) (Van Wagoner et al., 1990; Catuneanu et al., 2009). Shanley and McCabe (1994) recognized that maximum flooding surfaces within nonmarine successions are represented by tidally-influenced facies.

Flooding surfaces should never cross with other flooding surfaces or sequence boundaries; however, a sequence boundary can truncate or erode into a flooding surface and create the illusion of crossing surfaces. These flooding surfaces, along with sequence boundaries identified in outcrop can have similar well log characteristics. Despite these similar characteristics identified with stratigraphic profiles and nearby well logs, the surfaces and/or stacking patterns can change when moving either landward or seaway (i.e., marine shale will correlate in the landward updip section to estuarine and coastal plain strata and eventually to fluvial strata). This study has identified seven flooding surfaces and seven sequence boundaries within the Rollins Sandstone to lower Williams Fork interval and are summarized in detail in Table 1.7.

The coal zones within this study area directly overly marine wave-dominated shorefaces. This study marks this surface as a sequence boundary, indicating a basinward shift in facies. Coals zones identified in this study area range from 10 cm to 8 m. Based on an average peat to coal compaction ratio of 10:1, this thick coal deposit indicates a long-lived accumulation of terrestrial, organic matter within a peat bog, swamp, and/ or mire. Collins (1975) interpreted coals within the Cameo-Wheeler zone of the lower Williams Fork Formation to be primarily of low ash, low sulfur content with high volatile C, ranging from bituminous to anthracite coals. McCabe (1987) suggested that coals with low ash contents form away from active clastic depositional environments. Peat accumulation in close proximity to clastic environments such as beach-barrier systems, interdistributary channels, bays, levees on top of deltas, and meandering rivers are unlikely to have deposited thick peats with less than 50% ash, unless these were deposited in a raised mire (McCabe, 1987). Previous interpretations have associated these coal zones in close proximity to marine settings as conformable, Waltherian-shifts (Madden, 1989; Johnson, 1989; Tyler and McMurray, 1995; Hettinger and Kirschbaum, 2002; and Shaak, 2010). However, coals interpreted in a study in Alberta, Canada show that the thickest peat accumulated in mires 40 to 80 km landward of the paleoshoreline (McCabe, 1987). A modern analog to this would be from the Okefenokee Swamp in South Georgia, where low ash peat accumulations form in a mire 70-100 km inland from the present day Atlantic Ocean (Cohen et al., 1984, McCabe, 1987). This modern system is removed from river systems with clastic sediment, allowing for peat to accumulate. The mire directly overlies Pleistocene marine environments as well, indicative of a hiatus (Cohen, 1984). The study within the Alberta coal deposits illustrates that the juxtaposition of coastal sediments and thick coal deposits does not always suggest a raised mire (McCabe, 1987). In concurrence with this study, Patterson et al. (2003) has also interpreted a sequence boundary overlying the Rollins Sandstone Member. They observed lower shoreface sandstone deposits of the Rollins Sandstone Member cut by an irregular-based surface and overlain by coal of the Cameo Zone. Work presented by Sydow and Roberts (1994) show evidence which supports sequence boundaries marked at the tops of highly progradational deltaic systems within the lowstand system tract indicating a fall in base level.

2.7 Outcrop to Subsurface Connection

Extending the correlation from outcrop to subsurface initiated with identifying sequence-stratigraphic surfaces in each stratigraphic profile. The stratigraphic profiles were then compared to the nearest well log in order to examine well log characteristics and correlate between outcrop and the subsurface. Once these surfaces were identified in the well log, they could be extended into the basin to other wells. Difficulties arise when extending the correlation towards the west, when transitioning to more continental environments. A maximum flooding surface for example might be identified in marine shale out in the basin (highest GR response below a coarsening up package), however shifting landward along this same time surface will eventually correspond with more tidal and/or coastal plain environments (serrated, spikey, coarsening up well log pattern).

Eastern Piceance Basin (Paonia, New Castle and Meeker, CO)- The facies in the eastern part of the basin tend to show coarsening up packages up from the Top Cozzette Member (maximum flooding surface or MFS_B-RL_T-CZ) to the Rollins Sandstone Member (ranging from 300 ft to 700 ft thickness) and is marked with a sharp top with overlying terrestrial coal deposits, representing a basinward shift in facies (Figure 1.18). This surface marks sequence boundary 2 (SB_2) and typically shows the first low GR and very high RES response on well logs above the Top Cozzette/Base Rollins maximum flooding surface. A minor flooding surfaces was identified and mapped within this coal facies and shows a high GR response with typically, a serrated coarsening up trend (25-100 ft thick) with a sharp top. Above this surface are more thick coals and meandering fluvial deposits (100-200ft thick) and signifies a basinward shift again and sequence boundary (SB_3). Flooding surface FS_3 is located above sequence boundary 3 and marks a significant flooding surface in the eastern basin as the first major transgression of the Middle Sandstone Member within the lower Williams Fork Formation above the Rollins Sandstone Member. The flooding surface is distinguished by its high GR and low RES well log response and a thick marine shale interval in outcrop. The overall thickness of this zone (FS_3 to SB_3_5) varies from 50 to 200 ft. This interval (sequence 3) shows a clear coarsening up, shoaling up packages within a wave dominated shoreface and is capped by another terrestrial fluvial and coal coastal plain deposit (SB_3_5). Sequence boundary 3_5 is typically marked by a low GR and high RES well log response. Flooding surface 3_5 marks another high GR and low RES well log response at the base of a thin (50-75ft) coarsening up package identified in the south (Paonia, CO) located above the Top Middle Sandstone formation top in Figure 1.18. FS_3_5 is characterized by relatively thick (100-150ft) coarsening up package in the central and northeast (New Castle and Meeker, CO respectively). From sequence boundary 3_5 to sequence boundary 4 is characterized by transgressive, tidally-influenced estuarine deposits (i.e., bayhead deltas, tidal channels and floodplain) and is capped by more fluvial facies with low GR responses. Sequence boundary (SB_4) is picked at the base of blocky to slight fining up, fluvial, low GR package in parts of the southeast and northeast basin and more coal-rich coastal plain settings in the central east (near New Castle, CO) (Figure 1.18). Flooding surface 4 marks a significant surface throughout the entire basin as it is used as the datum for this entire study. This marks the transgression of the Upper Sandstone within the lower Williams Fork Formation. FS_4_TS surface is picked at the base of a high GR and low RES response and/or more shoreface marine deposits (as seen in the southeast basin in Figure 1.18). The FS_4_MFS surface is picked within marine shales and/or shoreface in the deepest water facies and on the highest GR and low RES response well log curve above sequence boundary 4. Sequence boundary 5 marks a shift from more tidally-influenced deposits to predominately fluvial and is picked at the base of a low GR sandstone. Flooding surface 5 is located stratigraphically above sequence boundary 5 and marks a landward shift in facies of coastal plain and tidal influence in the north and southeastern parts of the basin, and at the base of a wave-dominated upper shoreface deposit in the central east (New Castle, CO). The log patterns for FS_5 are typically characterized by high GR with a serrated coarsening up package overlying (25-100ft). Sequence boundary 6 marks another basinward shift in facies from tidally-influenced/marine to meandering fluvial and picked at the base of a low GR package. In the central east part of the basin near New Castle, tidally-influenced facies overlying fluvial successions mark flooding surface 6. In the north however, this surface corresponds to a rise in base level within the continental environments and marks a transition from more meandering fluvial to anastomosed rivers. Sequence boundary 7 is picked at the base of a low GR package and shows an overall change in the stacking patterns from stratigraphically below. Above SB_7 are thick (50-150ft) blocky sandstone fluvial packages.

Central Piceance Basin (Fruita, Grand Junction, Palisade, CO) - The lower bounding stratigraphic surface of this study (MFS_B-RL_T-CZ) in the central part of the basin marks a high GR and low RES well log response and shows a thinning to the west. From flooding surface MFS_B-RL_T-CZ to SB_2 ranges in thickness from 200-100ft and was picked at the base of a coarsening up shoaling up package. Sequence boundary 2 is distinguished in the central Piceance basin by the first coal (has a low GR and high RES response) package above the top Rollins and represents a basinward shift in facies. Flooding surface 2, stratigraphically positioned above sequence boundary 2, is characterized by undifferentiated floodplains and tidally-influenced deposits within the Cameo coal zone and is picked at the base of a serrated coarsening up package (15-50 ft thick) within a high GR response. Above flooding surface 2 is sequence boundary 3 (SB_3) with meandering fluvial deposits and undifferentiated floodplains deposits. Within well logs, SB_3 is picked at the base of a rounded to fining up sandstone package with a low GR. Flooding surface 3 marks a landward shift in facies which is characterized by tidally-influenced facies overlying meandering fluvial. The FS_3 surface is picked within a high GR response at the base of a serrated coarsening up package observed in data point 62 at 1500 ft in depth in Figure 1.18. Sequence boundary 3_5 is picked at the base of a low GR, fining up, meandering fluvial, sandstone package. About 20-50 ft above SB_3_5 is flooding surface 3_5 which signifies a landward shift of facies, and is picked at the base of a coarsening up, serrated package within a high GR well log response. Sequence boundary 4 (SB_4) is picked at the base of a low GR package which shows a blocky to slight fining up pattern. Above SB_4 shows the multi-story vertically-stacked meandering fluvial facies which overlies tidally-influenced facies and therefore marks a significant basinward shift in facies. The datum, or flooding surface 4 marks tidally-influenced and coastal plain facies above more continental fluvial deposits and represents a landward shift in facies. The FS_4 surface is picked within a high GR response below a serrated, coarsening up well log pattern. Sequence boundary 5 marks a landward shift in facies with more continental, vertically-stacked and single story meandering fluvial deposits above tidal. Flooding surface 5 (FS_5) shows tidally-influenced deposits to single-story isolated meandering fluvial channels with very thick floodplain deposits. FS_5 is picked within a high GR response however can be truncated and incised into by the above sequence boundary 6. Sequence boundary 6 is located above flooding surface 5 and is picked at the base of block to fining up sandstone in some places and incises into flooding surface 5 and sequence boundary 5 in some places within the central basin. Flooding surface 6 (FS_6) marks a change in base level and is represented by minor tidal influence, thick floodplains, and/or anastomosed fluvial complexes within with central basin. The FS_6 surface is picked within a high GR response with a serrated pattern indicating high mudstone content with minor interbedded sandstones. Sequence boundary 7 (SB_7) is picked similarly to how it is picked in the east at the base of a low GR, sandstone package in data point 62 at a depth nearing 1100 ft in depth in Figure 1.18. Above SB_7 shows are thick (50-200ft), blocky, amalgamated fluvial sandstone packages.

Western Piceance Basin (Mack, Douglas Creek Pass -Hwy 139, Rangely, CO) – Towards the west there is an obvious thinning of the stratigraphic study interval. The flooding surface at the top Cozzette (MFS_B-RL_T-CZ) is picked in a high GR and low RES response and marks a landward shift in facies from offshore marine (east and central) to tidally-influenced and coastal plain deposits (west). Sequence boundary 2 is picked at the top of the Rollins Sandstone and at the base of a low GR response from coal and single-story meandering fluvial facies seen at 11 ft in depth in data point 22 in Figure 1.18. Flooding surface 2 is represented by tidally-influenced deposits and marks a landward shift in facies within the Cameo coal zone. Sequence boundary 3 (SB_3) is picked at the base of a low GR, meandering fluvial system which can locally can be multi-story, vertically-stacked or have single-story channels. SB_3 however, is truncated by the above sequence boundaries SB 3_5 and SB_4 moving further west. Flooding surface 3 in the west is represented by tidally-influenced and undifferentiated floodplain facies and chosen within a high GR, serrated well log pattern which is cut into and not preserved west of East Salt Creek.

Sequence boundary 3_5 (SB_3_5) shows a basinward shift in facies and is picked at the base of a low GR, blocky to fining up well log response. Facies seen above the SB_3_5 surface are multi-story, vertically-stacked, and/or isolated single-story meandering fluvial channels. The SB_3_5 surface truncates the underlying SB_3 and FS_3near East Salt Creek and is truncated further to the west by SB_4. Flooding surface 3_5 has tidal influence in the west and/or documents a change in facies stacking patterns from vertically-stacked multi-story meandering fluvial to thicker floodplain mudstones and siltstones and isolated single-story meandering fluvial channels, suggesting a rise in base level and/or increase in accommodation. Flooding surface FS_3_5 is truncated to the west by sequence boundary 4. Sequence boundary and flooding surface 4 show similar responses and facies stacking patterns and their corresponding surfaces seen in the central part of the basin. Sequence boundary and flooding surface 5 is not present in the west due to truncation by the above sequence boundary 6. Sequence boundary 6 is marked by a basinward shift in facies (multi-story, vertically-stacked meandering fluvial overlying tidal-influenced and undifferentiated floodplain deposits) and picked at the base of a blocky to fining up, low GR response at a depth of approximately 640 ft in depth in data point 22 (Figure 1.18). Flooding surface 6 (FS_6) in the west is represented by anastomosed fluvial facies which suggests an increase in accommodation. The FS_6 surface is picked on a high GR response within a spikey sometimes coarsening up interval. Sequence boundary 7 in the west is represented by the same features chosen in the east and central parts of the basin and picked near 380 ft in depth in data point 22 (Figure 1.18).

1.8 Regional Sequence-Stratigraphic Correlation in the Piceance Basin

The approach for this study was to construct regional correlations along the margins of the basin in order to show the sequence-stratigraphic framework within the lower Williams Fork Formation. The following section consists of key observations from each regional correlation, and the distribution of lithofacies associations in a sequence-stratigraphic context with in the Piceance Basin. Five stratigraphic cross-sections are presented here; four of these follow the outcrop belt along the margins of the basin and one is through the center of the basin with outcrop tie-points on each end.

1.8.1 Depositional Sequences and Sequence Sets

The present study identified six regional depositional sequences and depositional sequence sets within the lower Williams Fork Formation of the Piceance Basin based on seven defined flooding surfaces. Previous ammonite and radiometric dating collected by Gill and Hail (1975) and Cobban et al. (2006) was utilized to provide age constraints for these depositional sequences. The total duration of time to deposit this interval ranges from 75.08 (+/- 0.11) Ma to 73.52 (+/- 0.39) Ma and is approximately 1.5 Ma. Therefore, one depositional sequence is roughly260 ky.

Ammonite data within this stratigraphic study interval has been previously collected and interpreted primarily in the eastern part of the basin. Madden (1989) shows ammonites *Exiteloceras jenneyi* and *Didymoceras cheyennense* at Rifle Gap and New Castle respectively (Appendix A). However, transitioning westward shows more nonmarine successions and does not have as well defined age constraints. Ammonite *Baculites compressus* was not identified in this study and speculated based on Johnson (1989) and Johnson and Flores (2003) stratigraphic nomenclatures. Roberts and Kirschbaum (1995) show that palynological data within this stratigraphic interval is broadly constrained within one palynomorph zone, *Auilapollenites quadrilobus* (Appendix A).

Based on Vail et al. (1977) and Miall (1990 and 2010), the six depositional sequences within this time interval are classified as high-frequency +/- 4th order sequences. Two depositional sequence sets were distinguished from these six sequences, which help to show larger scaled cycles and stacking patterns. Sequence set A consists of SB-4 to SB-2 and sequence set B is from SB-7 to SB-4. These two sequences are shown at the base of Figure 1.20. Based on the stacking patterns observed from the depositional sequences, sequence set A shows an overall more progradational stacking trend where the sequences show an overall basinward shift. Sequence set B shows an overall aggradational stacking pattern where the facies and parasequence stacking patterns are relatively consistent as they aggrade vertically over time. Within these depositional sequences show short transgressive-regressive cycles which account for extensive tidal and estuarine deposits identified in outcrop. However the overall stacking trends of sequence sets A and B represent longer, +/-3rd order cycles (approximately 750 ky) and are interpreted to be a part of a highstand systems tract.

1.8.2 Correlations

Five stratigraphic transects were correlated and interpreted for this study to show how lithofacies observed in outcrop correspond with well log characteristics in the subsurface in order to understand the basin-wide lithofacies association distributions in the basin. Each of the stratigraphic transects discussed below uses flooding surface 4 (FS_4) as the datum. This surface is associated with the lithostratigraphic unit of the Upper Sandstone within the lower Williams

Fork Formation typically observed in the eastern basin. The main observations and interpretations from these five sections are discussed in this section.

A-A'-This stratigraphic transect is oriented west to east and positioned along the southern margins of the Piceance Basin (Figure 1.20). Key regionally extensive flooding surfaces (MFS, TS) were mapped further west than previously interpreted, towards the Douglas Creek Arch within the lower Williams Fork Formation. Flooding surfaces within the older depositional sequences (Sequence-2, 3, and 4) show marine facies (wave-dominated shoreline deposits) transitioning landward to their correlative surface in the coastal plain and nonmarine (tidally-influenced environments and/or isolated, single-story meandering fluvial channels within a predominately floodplain-rich environment). However, stratigraphically through time, there is an overall basinward shift in facies and flooding surfaces identified in the upper part of the lower Williams Fork Formation are represented by tidal facies in the east and central part of the basin. Transitioning west, these surfaces are represented by purely nonmarine deposits of either anastomosed fluvial complexes and/or high floodplain concentrations with few isolated meandering channels. There is an abundance of truncated surfaces when moving west towards the DCA. The clustering of these sequences near DCA and Uncompahgre Uplift (UU) could be indicative of growth strata and illustrate active tectonism during sedimentation. Truncation and incision is also documented surrounding the Hunter Canyon area (data point 115). The above these downcutting surfaces (especially SB_3_5, SB_4 and SB_ 6), the facies associations typically show the following stacking patterns: multi-story, vertically- stacked, meandering fluvial deposits (associated with lowstand fluvial deposits), overlain with floodplain and isolated single-story meandering channels and/or tidally-influenced deposits (i.e., transgressive systems tract capped by the maximum flooding surface within tidally-influenced deposits), then overlain predominately by floodplain deposits, isolated single-story meandering fluvial channels and/or associated anastomosed complexes (high crevasse splay preservation) with paleosol development and increase in fluvial channels (highstand). This stacking pattern then repeats with more incision and amalgamated fluvial channel fill deposits. These stacking trends are consistent within previous interpretation of incised valley fill deposits (Boyd et al., 2006; Catuneanu et al, 2009). This also applies to stacking patterns seen within fluvial successions previously interpreted by Wright and Marriott (1993), Shanley and McCabe (1994), and Rhee (2006). Incision, especially when approaching the west (i.e., more continental facies), eustatic controls might not be the dominant influence. Thinning and truncation of sequences suggests coeval growth of structures and deposition, which could have also contributed to the downcutting of these surfaces. A change in gradient of streams due to uplift, creates accommodation around the structure. Near Hunter Canyon, there are interesting facies relationships documenting anastomosed fluvial complexes surrounding the Hunter Canyon area, while at Hunter Canyon, there is a thinning trend and it is dominantly meandering fluvial channel facies (Sequence 3, 4, 5 and 6).

B-B'- This transect is oriented from west to east through the center of the basin, from Hunter Canyon (data point 115) towards South Canyon Creek (data point 123) (Figure 1.21). It is important to note the 30 mile gap in data from data point 52 to data point 27. When correlating across this gap however, correlation began at the margins with stratigraphic profiles and then correlated into the center, following the criteria set by Table 1.7. This correlation thickens to the east, towards the basin showing coarsening up, progradational, wave-dominated sandstone packages within the lower sequence set A (consisting of sequence 2, 3, 4). Within sequence 3, is evidence of the trangressive-regressive pattern within the lithostratigraphic unit, the Middle Williams Fork. Following flooding surfaces 3 and 3_5, show really good examples of serrated, coarsening up packages of bayhead deltas/ transgressive deposits further west within the lower Williams Fork Formation. Above, sequence set B (sequences 5, 6, and 7) show an aggradational stacking pattern with the transgressive-regressive Upper Sandstone and increase in mudstone-rich facies of floodplain deposits.

C-C'- The C-C' transect is located in the northern part of the basin, trending west (Rangely, CO) to east (Meeker, CO) (Figure 1.22). Thinning is observed in the west, especially due to incision from sequence boundaries 4, 6, and 7. This thinning and more prevalent incision in the northwest of the basin could be influenced by growth development and uplift of the Uinta Mountains (UMU). Tide-influenced facies helped identify regionally extensive flooding surface in the north within sequences 2, 3, 4, and 5 (flooding surfaces 2, 3, 3_5, and 4). However, tide-influenced facies in the northeast are only observed in the Devil's Hole section within depositional sequence 6 (flooding surface 5) and is mapped westward through higher accommodation fluvial cycles such as high floodplain, anastomosed, and /or isolated, single-story channel deposits.

D-D'- This stratigraphic transect is divided into two parts: part one (north) trends north to south along the northeastern part of the basin (see Figure 1.23) while part two (south) is north-south trending in the southeast (Figure 1.24). These cross-sections are broadly orientated parallel to the paleoshoreline. From D-D' part 1 to part 2 shows an overall thinning of the depositional sequences interpreted in this study. These correlations along the eastern margin of the basin document a transition from predominantly marine to tidally-influenced to fluvial facies from the oldest to youngest depositional sequences. This stratigraphic transition from marine to fluvial facies suggests shows an overall progradational to aggradational stratigraphic stacking trend. For example, wave-dominated shoreface deposits are found predominately within the oldest three sequences (2, 3, and 4) and show an overall thinning stratigraphically with more tidally-influenced facies and coastal plain environments.   The younger depositional sequences observed within sequences 5, 6, and 7, transition to mostly undifferentiated floodplain deposits, anastomosed and/or single-story meandering fluvial channel complexes with some tidal influence. These younger depositional sequences tend to show these same stacking patterns in this east.

E-E'- The stratigraphic transect of E-E' is divided into two parts to show the complexities along the western margins of the basin near the Douglas Creek Arch (DCA). These two transects are positioned to the east and west of the DCA and oriented north (Rangely, CO) to south (towards the Book Cliffs). Difficulties arise as these transects are not oriented in the direction of stratigraphic dip and also are over a structure. In order to capture key sequence-stratigraphic trends however, these transects were chosen on the eastern side (Figure 1.25) and western side (Figure 1.26) of the structure, oriented from north to south. Both transects show a thinning to the south, towards the Book Cliffs especially over the DCA (data points 118 and 68), and in the south, near data points 13, 17 and 112). East of the DCA shows onlapping relationships of flooding surfaces 3 near data point 68 and near 17 and 112. The truncation of depositional sequences 3 and 4 by sequence boundary 4 is pronounced at locations at 70 and 17. Sequence boundary 6 truncates depositional sequence 6 towards the south. The thickening and thinning or folded strata of depositional sequences seen in the northern area (data points 95, 93, 80, and 67) along the east transect (Figure 1.25) is due to the location of data points alternating from closer to further away from the structure or possibly from different zones of the DCA structure uplifting at different times The data points to the west of the structure are limited and at the edge of the data set, however show a thinning trend towards the DCA and UU structures (Figure 1.26). The intensity of truncation of surfaces, syntectonic unconformities, onlapping surfaces near areas of known structures, as well the high concentration of multi-story, vertically-stacked, meandering fluvial facies (indicative of low accommodation) suggests that this area was actively uplifting during deposition of the lower Williams Fork Formation.

1.8.3 Basin-Scale Distribution of Lithofacies

The 9 lithofacies associations identified in the stratigraphic interval of this study (Rollins Sandstone Member to lower Williams Fork Formation) show interesting stratigraphic and geographic distributions throughout the Piceance Basin. Depositional sequence 3 shows the lateral distribution of facies along correlation A-A' from more fluvial to marine environments (Figure 1.20). In this section, each of these associations will discuss observations, interpretations and patterns regarding the geospatial distribution in basin. Two gross depositional maps of sequence set A (Figure 1.27) and sequence set B (Figure 1.28) represents a general idea of how the depositional environments change spatially in the basin.

Facies Association A: Multi-story, Vertically-Stacked, Meandering Fluvial

Facies association A is more prevalent in the western part of the basin near the DCA, Rangely, and Fruita/Grand Junction areas. This facies association has been identified in all of the sequences of the study, however, this association is concentrated in the west in the older sequences (sequence 2 and 3) and migrates east towards the WIS in the younger sequences (sequences 4, 5, 6, and 7).

Facies Association B: Isolated, Single-Story, Meandering Fluvial

This facies is primarily identified in the western part of the basin in the older sequences (sequence 2, and 3). Stratigraphically, these facies shift eastward. Sequences 4, 5, and 6 document isolated, single-story, meandering fluvial complexes as far east as data points 116 (Kannah Creek/Lands End section) and 119 (Moyer-Hwy13 section). During sequence 7, this facies is distributed throughout the entire basin.

Facies Association C: Anastomosed Fluvial Complex

Anastomosed fluvial channels are not identified in the younger sequences and are only present in sequence 5, 6, and 7. Sequence 5 shows this association southeast of the Hunter Canyon area (data point 115) while sequences 6 and 7 show anastomosed complexes in both the north and south regions of the basin. In the south, this association is found to northwest and southeast of Hunter Canyon. In the north however, this anastomosed complexes are found near data point 110 and 71.

Facies Association D: Undifferentiated Floodplain: Coastal Plain and/or Fluvial Floodplain

As this facies association is generalized to suspension deposition and flood plain deposits, it is documented in all sequences within found within all the sequences and not designated to one specific location.

Facies Association E: Tidally-Influenced Channels within Estuary or Deltaic Environment

Sequences 2, 3, and 5 documents tidal influence as far west as data points 17 and 124 (south and north respectively). Stratigraphically over time, these facies are typically only found in the central and eastern regions of the basin.

Facies Association F: Estuarine, Tide-Influenced BayHead Delta

This transgressive, estuarine, tide-influenced bayhead delta association is only observed in sequences 2, 3, 4, and 5. These deposits are primarily documented along the eastern margins of the basin, typically near shoreface deposits. However, sequence 2 identified this association reaching as far west as data points 124 (in the northern part of the basin) and 47 and 20 (in the south).

Facies Association G: Upper Shoreface to Foreshore

The upper shoreface to foreshore facies association is documented within sequences 3, 4, 5, and 6. Within sequence 3, this association is mainly in the southeast, however it can extend as far west as data points 121 and 49. Sequence 4 shows that this association found in the south east, near data points 113, 21, and 10. This association is documented in sequence 5 along the eastern margin of the basin, however is also identified further west in the southern part of the basin near data point 49. This location shows the classic coarsening up, sharp tops well log signatures associated with wave-dominated shoreface sandstones. This facies association also has a minor present in sequence 6, near New Castle, CO.

Facies Association H: Middle to Lower Shoreface

Facies association H within sequence 3 was observed primarily in the southeast margins of the basin. Sequence 4 shows the middle to lower shoreface association also along the southeast margin of the basin near data points 128 and 64. Sequence 5 documents this association in the northeast (near Meeker, CO, data point 110) and southeast (near New Castle and Redstone, CO). Middle to lower shoreface deposits were documented primarily along the eastern margins of the basin.

Facies Association I: Offshore Distal Lower Shoreface to Lower Shoreface

Sequence 3 shows offshore to lower shoreface deposits in the north (near data point 63) and along the southeast margin of the basin. Within sequence 4, this environment was only identified in the southeast near data points 113, 10, 64. Sequence 5 was mainly distributed along the eastern margin in the north (data point 110) and southeast margins (data points 113, 14). The offshore to lower shoreface environment was only observed within three sequences (sequences 3, 4, and 5) and was only documented along the eastern margin of the Piceance Basin.

1.9 Thickness Trends

Three isopach maps were generated in this study to show basin-wide thickening trends in the Piceance Basin from the Rollins Sandstone through lower Williams Fork Formation interval. The observations and interpretations for each are described hereafter, beginning with total thickness trends, followed by the oldest sequence set to youngest of the stratigraphic study interval.

1.9.1 SB-7 to SB-2 (Total): Isopach Data

Description- This interval represents the entire stratigraphic study interval and includes the total thickness from sequence boundary 7 through sequence boundary 2 (Figure 1.29). The isopach map shows an overall thickening towards the northeast (Meeker, CO), reaching a maximum thickness of 2200 ft. There is a thinning towards the Utah-Colorado state line in the west and southwest part of the basin, near the Douglas Creek Arch (DCA) and Uncompahgre Uplift. At Hunter Canyon (data point 115) near Fruita, CO, there are thicker, elongated zones oriented NE-SW on the east and west sides of the Hunter Canyon area. Near the Douglas Creek Arch there are undulatory thin zones surrounding the arch and have a north-northwest to south-southeast orientation.

Interpretation- The thickening towards the northeast shows the overall direction of sediment transport was to the northeast towards the Western Interior Seaway. Thinning towards the west approaching the DCA suggests that this structure was uplifting during time of deposition. The undulatory thinning pattern seen in the west near the DCA could be indicative of some parts of the DCA uplifting while other parts of the structure were inactive. The thinning patterns show the parts of the structures that were active during the deposition of that particular packet of sediment. The thinning trends indicate the DCA has a north-northwest to south-southeast orientation, which is almost parallel with the orientation of the basin depocenter. This orientation differs from previous orientations which show the DCA to be oriented north-south (Tweto, 1979; Cumella and Cole, 2003; Mederos et al., 2005; Miller, 2011).

The elongated, thicker zones near the west and east sides of the Hunter Canyon are interpreted as incised valley deposits which drained to the northeast to the Western Interior Seaway (Figure 1.29).

The overall thickening and thinning trends observed within this stratigraphic interval shows interesting relationships in respect to the geographic distribution of producing gas fields in the Piceance Basin. Many of the producing fields correspond relatively well with the thickening trends (Figure 1.30). Near the Plateau gas field there is a relative thick zone north of the east-west thinning in the southern part of the basin (data points 51, 53, 57, 48). This could represent sediment accumulation and accommodation which occurred around structures developing during time of deposition in the south. Using a cutoff at 95 API on the digitized curves in this study, net-sandstone maps were generated in order to show the relation between thickening and if there is any correspondence with sandstone accumulation. However, due to not all of the wells logging through this stratigraphic interval, fewer wells were used to generate these maps (80 data points, see Appendix B), therefore caution must be taken when viewing anomalous thick and thin trends ("bulls-eyes"). Based on the net sandstone map from SB-7-SB2, there seems to be thicker sandstone intervals found in the east, which interestingly align with some of the well-known gas fields in this region (i.e., Mamm Creek, Parachute, Grand Valley, etc.) (Figure 1.31). Towards the west however, there is also thicker sandstone accumulations, which are interpreted to be associated with thicker and multi-story vertically-stacked meandering fluvial deposits, which have a high net to gross sandstone ratio. Based on the combination of isopach thickness trends with local sandstone-rich zones shown in the net sand maps, new areas that have potential to be productive are circled in black in Figure 1.31.

1.9.2 SB-4 to SB-2: Isopach Data

Description- This isopach shows the overall thickening trends from depositional sequences 2, 3, and 4 (Figure 1.32). There is an overall thickening towards the north and northeastern parts of the basin, reaching thickness greater than 900 ft thick. Thinning is clearly seen in the DCA area; however, slight thinning trends are also observed near Meeker, CO, and the Hunter Canyon and Coal Canyon stratigraphic profile locations (data points 115 and 109). Slight thickening occurs to the sides of these thin zones near 115 and 109. The DCA also shows an irregular, undulatory thinning pattern in the west with thin arms branching away from the structure.

Interpretation- The apparent thickening towards the east and northeast shows the overall direction of sediment transport and depocenter of the basin during this time in the Campanian. Thinning in the west and south are interpreted to be influenced by the uplift of the DCA, Uncompahgre (UU), and nearby reactivated Pennsylvanian/Permian Structures (Figure 1.32). The slightly thicker zones within the thin branches help confine the paleoflow of incised valley, which were later filled with trangressive deposits (Figure 1.33). These thin arm branches could also be an imprint of the timing of different parts of the structure. However, caution must be considered as these features are near the edge of the data set. Thins near Meeker, CO could be attributed to the initiation of the White River Uplift (WRU) however, there are fairly extensive gaps in data surrounding these thin trends and these same thinning patterns are not identified in the younger SB-7 to SB-4 isopach, therefore this is a speculative interpretation.

1.9.3 SB-7 to SB-4: Isopach Data

Description -This isopach maps shows interesting thickness variations from sequence boundary 7 to sequence boundary 4 (Figure 1.34). This map illustrates a thickening to the northeast, towards Meeker, CO approaching a maximum of 1300 ft. There is a thinning in the west, northwest, and southwest parts of the basin which has an undulatory shape along the western margins (from Rangely to east of Grand Junction). These thin areas branch off from the structure in lineated features, oriented towards the east, near data points 77, 67, 18, and 45 (Figure 1.35). On either side of these thin, lineated branches, there is a slight thickening. There are some thick zones along the eastern margin of the basin which also have an undulose appearance.

Interpretation – The thickening trend towards the northeast indicates the direction of paleoflow of sediment transport. Thin zones in the west, northwest, and southwest suggests uplift of the DCA, Uinta Mountain Uplift (UMU) and potentially the Uncompahgre Uplift (and/or other Pennsylvanian-Permian structures that reactivated during the Laramide-style uplifts) were active during this time and affecting the depositional patterns throughout the basin. The undulose nature along the eastern margin of the basin represents the average paleoshoreline during this time in the Campanian. Areas of thick zones in the east (data points 120, 33, 106, 84) corresponding to the thick drainage zones in the west (data points 47, 60, 61, 71, 80, 108, and 112) and are interpreted to be associated with incised valleys and incised valley fill deposits.

1.9.4 Net Sandstone Trends

Thickness trends within each depositional sequence give insight into sequence-stratigraphic trends, as well as structural timing and development. By running statistics on one of these isopachs, an understanding of how and why sandstone is more prevalent in one area than another can assist with identification of better production locations. A net sandstone map was generated to compare with the total isopach interval (SB7-SB2) (Figure 1.31). This net sandstone map only utilized 80 of the digital GR well logs (see Appendix C for net-sandstone well list). In order to determine the net sandstone accumulation within the total stratigraphic study interval of the basin, a sandstone cutoff was applied at > 95 API (mean average GR cutoff value based on the statistics from the 80 well logs within PETRA™). The thickest sandstone accumulations are located in warmer tones and found in the north, east (along the Grand Hogback), and trending west to east in the central east part of the basin near data points 35 and 25. In the east, the map shows a thick sandstone accumulation which corresponds with the current location of producing gas fields. High sandstone accumulation within the basin could be indicative of paleoflow and location of the main migration pathways of depositional systems.

1.10 Discussion

There are three main topics of discussion regarding this study: (1) the complexities of applying sequence stratigraphy within the marine to nonmarine transition (2) the timing and development of structures influencing depositional systems within the Piceance Basin and (3) implications to tight-gas sandstone reservoirs.

Complexities with Sequence Stratigraphy in Nonmarine Successions

Fluvial systems respond to both allocyclic (i.e., eustasy, tectonism, and/or climate) and autocyclic (i.e., channel avulsion) processes and distinguishing between the two can be extremely challenging (Shanley and McCabe, 1994). Through previous studies, key criteria for approaching sequence stratigraphy in fluvial successions have been identified and summarized by Miall (2002) and are as follows: (1) fluvial incision occurs during base-level fall, (2) fluvial aggradation occurs during base-level rise, (3) tectonism and eustasy are the primary causes for base-level shifts in fluvial systems, (4) low-sinuosity, braided rivers occur during low accommodation, (5) anastomosed fluvial systems are associated with base-level rise (i.e., transgression), (6) highly-sinuous meandering fluvial systems represent low to moderate base-level rise, (7) Straight fluvial systems are characterized by low slope and low accommodation, (8) incised valleys can be filled by all fluvial system types, (9) Marine influence within fluvial systems (i.e., tidal signatures) represents transgression.

In this study, the identification of facies stacking patterns (especially within fluvial successions) with respect to accommodation was critical for identifying and correlating sequence-stratigraphic surfaces. For example if a tidally-influenced facies was overlain by a multistoried, vertically-stacked meandering fluvial complex within an overall continental environment, the tidally-influenced facies represent a flooding surface, while the overlying, vertically-stacked fluvial complex shows decreasing accommodation trends up section and would be marked as a sequence boundary. Facies stacking patterns in outcrop were comparable to nearby well log curves in the subsurface (Figure 1.18) and tend to show fluvial stacking patterns shifting from high accommodation to low accommodation. This study shows tidally- and marine-influenced facies observed in outcrop throughout the basin within most of the lower Williams Fork Formation which were identified further west than previously interpreted. Tidally-influenced facies significantly helped when applying sequence stratigraphy within nonmarine successions as they represent maximum flooding surfaces (Shanley and McCabe, 1994). However, moving up stratigraphically and towards the western part of the basin, these tidally-influenced facies were sparse or not present and were represented by a corresponding base-level rise within fluvial facies (i.e., anastomosed, high aggradation of floodplains, and/or isolated, single-story, meandering fluvial complexes).

Local downcutting of sequence boundaries near the Hunter Canyon area (data point 115) are interpreted as incised valley fills and show the classic facies stacking pattern of amalgamated, lowstand fluvial deposits, overlain with tidally-influenced facies and floodplain deposits (transgressive or a rise in base level), and finally, floodplain (more paleosols identified), and isolated, single-story meandering fluvial deposits, increasing in channelization stratigraphically due to a decrease in accommodation (highstand or a fall in base level).

Timing and Development of Structures in the Piceance Basin

Previous work constrains the timing of Laramide-style structures within the Cordilleran Foreland Basin from Late Campanian to Paleocene time. Cobban et al. (2006) shows the Campianian time ranges from 80 Ma to 70 Ma. The lower Williams Fork Formation is interpreted to have been deposited form 75 Ma to 73 Ma and is confined within the period of the development of Laramide-style structures (Late Campanian to Paleocene). However, this is a broad time interval and therefore cannot be used as the main argument for structural development during deposition of the lower Williams Fork Formation and therefore other criteria must be utilized.

Recognizing concurrent structural development and sedimentation is recognized by the following signatures as discussed in Frostick and Steel (1993) and Aschoff (2008 in review): growth strata (progressive, syntectonic unconformities), thinning near the structure (s), detrital compositions, paleocurrents deflection, spatial lithofacies patterns, clastic progradation, and stacking patterns in relation to accommodation and sediment supply. Of these, growth strata, thinning patterns, paleocurrent deflection and facies stacking patterns were the main signatures document and interpreted in this study. Growth strata was not identified in outcrop in this study, however, thinning and truncation of sequence boundaries utilizing well log data shows a good indication of growth strata. Similar to sequence stratigraphy within nonmarine strata, the recognition of facies stacking patterns is just as equally important. Most of the facies identified in areas near the structures (DCA, UU, and UMU) were predominately highly amalgamated, vertically-stacked, fluvial channels associated with low accommodation.

Johnson and Finn (1986), Mederos et al. (2005), and Bader (2009) suggest that the DCA began uplifting during the Campanian through the Late Paleocene to Early Eocene. High resolution sequence stratigraphy from Aschoff and Steel (2011a) show thinning trends from another Laramide structure in the Cordilleran Foreland Basin near the San Rafael Swell (central Utah). Their work shows evidence of uplift as early as 77 Ma in central Utah. These studies lead to the interpretation that Laramide structures may be older, with a longer kinematic history than previously recognized.

The isopachs generated from this study show an overall thickening towards the northeast, while thinning to the west. Isopach SB4-SB2 thins in the west and southwest parts of the basin. Based on the facies stacking patterns which show an overall decrease in accommodation, and downcutting of sequence boundaries, provides evidence which suggests that the Douglas Creek Arch and Uncompahgre Uplift were active during this time. There is limited data in regards to the timing Douglas Creek Arch and Uncompahgre Uplift within the lower Williams Fork Formation. However, isopach maps generated by Johnson and Finn (1986) show 4 stages of the development of the Douglas Creek Arch which indicate initiation of the uplift during the Campanian. Mederos et al. (2005) propose that the DCA was not reactivated by Laramide-style structures, but instead by large-scale folding due to lack of pre-existing basement-controlled structures. Bader (2009) work suggests that the Douglas Creek and Garmesa fault zones were continuous structural discontinuities that span from Precambrian time to more recently within the late-Laramide tectonism. This deformation has compressional (sinistral shear with associated normal faults and parafolds) and was then followed by an extensional domain (dextral shear from faulting). These two styles of deformation seem comparable as to the different timings seen within this study (Figure 1.32 and 2.34)

The Uncompahgre Uplift (covering approximately 4500 square miles) trends west to northwest and is located southwest of the Piceance Basin (Figure 1.7B) (Stone, 1977). This uplift is bounded in the south by the Uncompahgre fault zone and in the north by the Garmesa fault zone. Stone (1977) concluded that the main phase of uplift of the Uncompahgre was during the late part of Middle Pennsylvanian and continued through the Permian. This uplift however, was then reactivated during the Upper Triassic and Jurassic times along these faults north and south of the uplift. These units thin slightly over the structure; however no thinning of Cretaceous or

Tertiary stratigraphy was documented (Stone, 1977; Bump et al., 2003). Two cross sections through the Uncompahgre Uplift were interpreted by Scott et al. (2001) and show reverse faults post-dating the Jurassic (Wingate Formation), illustrating structural development through the Mesozoic. These cross sections also show indistinct thinning towards the structure in the Mancos Shale. Data is sparse within this stratigraphic study interval, and has not been preserved, which leaves much speculation to the influence of the Uncompahgre Uplift to have on sedimentations patterns within the lower Williams Fork Formation. Also, thinning observed near the Uncompahgre Uplift might not necessarily correspond to growth strata and could be a result of draping. Draping stratigraphy results of differential compaction. Due to thick accommodation space surrounding an intrusive allows for sediment accumulation and through time, these units will decompact around the structure.

Thinning shown in isopach SB7-SB4 shows thinning in the northwest, west, and southwest parts of the basin. These thinning patterns to the northwest are interpreted to be associated with the uplift of the Uinta Mountains. Bader (2009) interpreted the Uinta Uplift to have been activated during the Paleocene through Eocene time however; the work of Rountree (2011) in the Uinta Basin (west of the Piceance Basin) identified thinning trends near the Uinta Mountain Uplift within the depositional sequence from 75-74.9 Ma. This provided evidence that the Uinta Uplift was active as early as 75 Ma, much earlier than previously thought.

Implications for Tight-gas Sandstone Exploration and Production in the Piceance Basin

Reservoir heterogeneity is one of the main controls on the number of wells required to produce gas from the Iles and Williams Fork formations. Depositional facies provide some first-order insight into reservoir heterogeneity. Five facies associations have the best reservoir potential based on their internal heterogeneity and lateral extent and are number best to worst: (1) upper shoreface to foreshore deposits, (2) anastomosed, (3) multi-story, vertically-stacked meandering fluvial, (4) single-story meandering fluvial, (5) tidal channels deposits within incised valleys. Understanding heterogeneity of these five facies can impact fracturing methods when producing in the basin. Different lithologies have different fracture properties and can behave differently. For example, fractures within sandstones typically are spaced the same distance as the thickness of the bed (Bai et al., 2000) however, these fractures can be deflected when moving across a shale bed (Meckel, 2009, personal communication).

Although porosity and permeability measurements were not collected in this study, the shoreface sandstones tend to show the best sorting, maturity, porosity, and continuity and overall reservoir quality. Unfortunately, “blanket” shoreface sandstone deposits within the Iles

Formation can be water-wet (Brown et al., 1986). Discontinuous, fluvial deposits within this stratigraphic interval are the most productive reservoirs within the Piceance Basin with porosities ranging from less than 5% to 8% (Johnson and Roberts, 2003). Each of the fluvial reservoirs has some level of heterogeneity for example, isolated single-story meandering channels and anastomosed fluvial channels and crevasse splays are typically confined within floodplain deposits and/or interbedded with higher concentrations of mudstone. Multi-storied vertically-stacked meandering fluvial complexes were characterized as very thick, interconnected amalgamated fluvial deposits with a high net to gross sandstone ratios. However, these facies were deposited during low accommodation and are interpreted to have cannibalized most floodplain and organic-rich overbank deposits. This can hinder migration of gas due to further distance it is away from the source rock. Scoured surfaces and conglomerate, clast-rich, poorly sorted sediments at the base of these fluvial channels could also hinder migration of gas therefore, it is necessary for this facies to have good fracture networks in order to be economic.

Pranter et al. (2009) measured the dimensions of fluvial sandstone bodies using LIDAR. Mean averages from their studies showed crevasse splays to be 5.1 ft thick, 231.1 ft wide, and a width to thickness ratio of 94.6. Single-story channel bodies were on average 12.3 ft thick, with 339.5 ft wide, and a width to thickness ratio of 44.7 while multi-story channel bodies averaged a thickness of 19.1 ft, 512.3 ft wide, and 45.8 for the width to thickness ratio (Pranter et al., 2009). Tidally-influenced deposits such as the incised valleys and bayhead delta facies recognized and identified in this study, could also be important economic reservoirs within the basin (Boyd et al., 2006). Tidally-influenced deposits identified in this study are typically characterized by flaser, wavy, lenticular, or sigmoidal bedding and/or inclined heterolithic strata which all are highly interbedded with mud drapes, causing barriers and baffles to flow of gas. What makes both of these fluvial and tidally-influenced reservoirs productive is that they are proximal to the source rocks and/or depending on the location, highly fractured zones (Johnson and Flores, 2003).

These heterogeneous reservoirs can also vary stratigraphically and geographically through the basin. This study identified that the floodplain facies association can be found within all depositional sequences. The floodplain facies, facies association D, is composed of organic-rich mudstones, siltstones, and coal. The coal zones within the basin are where most of the gas is generated from (Yurewicz et al., 2003). Coal zones are found within this floodplain facies (association D) where the thickest coal accumulations are predominatly found within sequence 2 (within the Cameo-Wheeler coal zone) and in the eastern part of the basin within older sequences (sequences 2, 3, and 4) stratigraphically above and landward of wave dominated shoreface facies (facies associations G and H). Cross (1988) showed with numerical models how the distribution of major coal deposits tends to stack vertically and are typcially found above strongly progradational events. The marine upper shoreface reservoirs are stongly progradational, distributed along the eastern margin of the basin, and are only identified within depositional sequences 1, 3, 4, 5, and 6. The conclusions from Cross (1988) seem to also be applicable to this basin since the older sequences (especially sequence 2, 3 and 4) have thick and high accumulations of coal deposits located above and/or landward of strongly progradational environments. Interestingly, most of the major producing fields in the Piceance Basin are found in the cental and eastern parts of the basin where these thick coal accumulations would be distributed. The second best facies with good reservoir potential is the anastomosed fluvial complex which consists of thick floodplain fines, deep (4-8 m) confined channels with minor lateral variability, and higher preservation of crevasse splay deposits. Anastomosed channels were mainly documented within the younger depositional sequences (sequence 5, 6, and 7) and are recorded in the west, typically near potentially active structures. As anastomosed systems are characterized by a rise in base level, thin organic-rich mudstones and coals were identified near association C. This proximity of coal to anastomosed channels and splays is good for gas migration to these reservoirs. The third best reservoir is the multi-story, vertically-stacked meandering fluvial channels which are predominately in the west and located at the base of incised valley fill deposits or decreased accommodation. Incised valley fill deposits are mainly located within thicker, elongate zones branching away from the DCA and UU, and follow the fairways shown in Figures 2.31 and 2.33 oriented northeast. The fourth reservoir identified was single-story meandering channels (facies association B) which occur in all sequences and can be distributed anywhere in the basin. However facies association B reservoirs become more prevalent up section and are typically located on the western half of the basin. The final reservoir identified consists of tidally-influenced deposits. These are very heterogeneous due to high mud drapes but occur within incised valley fill deposits where some tidally-influenced channels might also be produced in conjunction with the other reservoirs within.

The nature of natural fractures and/or how these five identifed associations react to stimulated, fracture-induced methods also influences the rank and qualtiy of these potential reservoirs. Lorenz and Finley (1989) discuss how there are two types of natural fractures: (1) fractures from local faulting and/or folding which can cut across different lithologies and (2) fractures caused by low magnitude regional stresses from high pore pressures with little to no offset. The type two natural fractures are commonly controlled by differences in stresses due to changes in lithologies and therefore changes in the depositional environments control the reservoir heterogeneity and in turn affect the fracture distribution and production. Lorenz and

Finely (1989) identified four different depositional environments and hence four different reservoir types within the multi-well experiment (MWX) study which were: (1) shallow-marine "blanket sandstone" reservoirs, (2) paludal lenticular sandstone reservoirs, (3) coastal lenticular sandstone reservoirs, and (4) meandering fluvial sandstone reservoirs. Core, well-test data, and outcrop analysis was utilized to assess and characterize the nature of fractures identified between the four different depositonal environments. Their data concluded that type 1 has widely spaced, variable distribution, with good fractures communication and unlimited vertical fracture heights is benefical to production. Type 2 has high fracture quantities which enhance permeabilities within the reservoir, hwoever these fractures are not as interconnected as those in type 1 and typically only enhance permeabilities in one direction. Type 3 has tends to have smaller, yet more frequent fractures however, with more mineralization is common. Finally, type four shows two distinct fracture patterns: one without intersecting fractures (in the lower fluvial zone) and one with good interconnected fractures and good productions rates (middle fluvial zone) (Lorenz and Finley, 1989).

Fracturing methods used in the Williams Fork today primarily consist of perfing wherever a sandstone or low GR reading is present in the well log throughout the entire formation. This in turn makes it difficult to discern which facies association has the best reservoir characteristics (Anderson, 2011, personal communication). Davis (2007) and others working this basin have concluded that the best permeability occurs when hydraulic fracture stimulation links to the natural fracture networks where "sweet-spots" with high natural fracture densities can yield two to three times the average expected ultimate recovery (EUR).

Isopach and net-sandstone maps show thickening in the eastern part of the basin which supports the interpretation of incised valleys filled deposits with fluvial and tidally-influenced channels in an east to northeast orientation. These thickness trends identified within this stratigraphic interval tend to correspond with some of the major producing gas fields within the Piceance Basin. A net-sandstone map was generated for the total stratigraphic study interval (SB-7 through SB_2) in order to compare statistically the amount of sandstone associated with the thicker areas highlighted in these isopach maps. Sediment transport and fairways were mapped out based on thickness trends observed in isopachs SB 4-SB2 and SB7-SB4 (Figures 2.33 and 2.35). When mapping the net-sandstone through the stratigraphic interval, only some of these thicker zones corresponded with high net-sandstone accumulations. Interestingly enough, some of the highest net-sandstone accumulations corresponded well with producing fields along the I-70 corridor (Mamm Creek, Rullison, Parachute fields) (Figure 1.31). Other potential productive areas identified in this study that show high sandstone accumulations along sediment fairways mapped in Figures 2.33 and 2.35 could be places for future development and production.

Caution must be applied when interpreting and/or deciding where to drill for the next big gas field in the basin and shouldn't be based on thickness trends in the net sandstone thickness map alone. As mentioned previously, the data utilized to generate this net sandstone map were 80 well logs; however these data points are primarily concentrated along the margins of the basin.

It should be noted that certain types of facies and facies distributions can be more confined to a certain part of the basin than others. For example, the thick sandstone accumulations observed in the northwest are most likely due to the higher concentration of facies association A (multi-story, vertically-stacked meandering fluvial channels). Coals were not flagged within this GR cutoff and are therefore included in the net sandstone thickness calculation; hence a thick sandstone accumulation could be mistaken for a thick coal zone.

1.11 Conclusions

The regional sequence-stratigraphic framework of the study interval (Rollins Member of the Iles Formation through the lower Williams Fork Formation) within the Piceance Basin initiated with detailed lithofacies and interpretation of depositional systems in outcrop. Identifying facies stacking patterns and surfaces within stratigraphic profiles made it possible to correlate to nearby subsurface well logs. By developing relationships from outcrop to subsurface, key stratigraphic surfaces identified in outcrop were then utilized to correlate regionally in order to establish a detailed sequence-stratigraphic framework through the basin. The conclusions from this study are as follows:

Through this study, 34 different lithofacies were described, interpreted, and assigned to nine lithofacies associations. Each of these nine lithofacies associations was assigned within all of the newly measured stratigraphic profiles in order to visually display the stratigraphic changes and depositional environments within the basin.

By utilizing both stratigraphic profiles and subsurface well logs in the correlations, six depositional sequences were identified in the study. Within each of the six depositional sequences, seven regional flooding surfaces were identified and correlated through the basin. These surfaces are represented by either tidally-influenced facies and/or facies with thick floodplain deposits and/or anastomosed fluvial complexes (signifying an increase accommodation due to changes in base level). These facies and surfaces were observed within nonmarine fluvial successions, west of the paleoshoreline of the Western Interior, and identified based on five distinct fluvial facies stacking patterns, showing overall trends of decreasing accommodation.

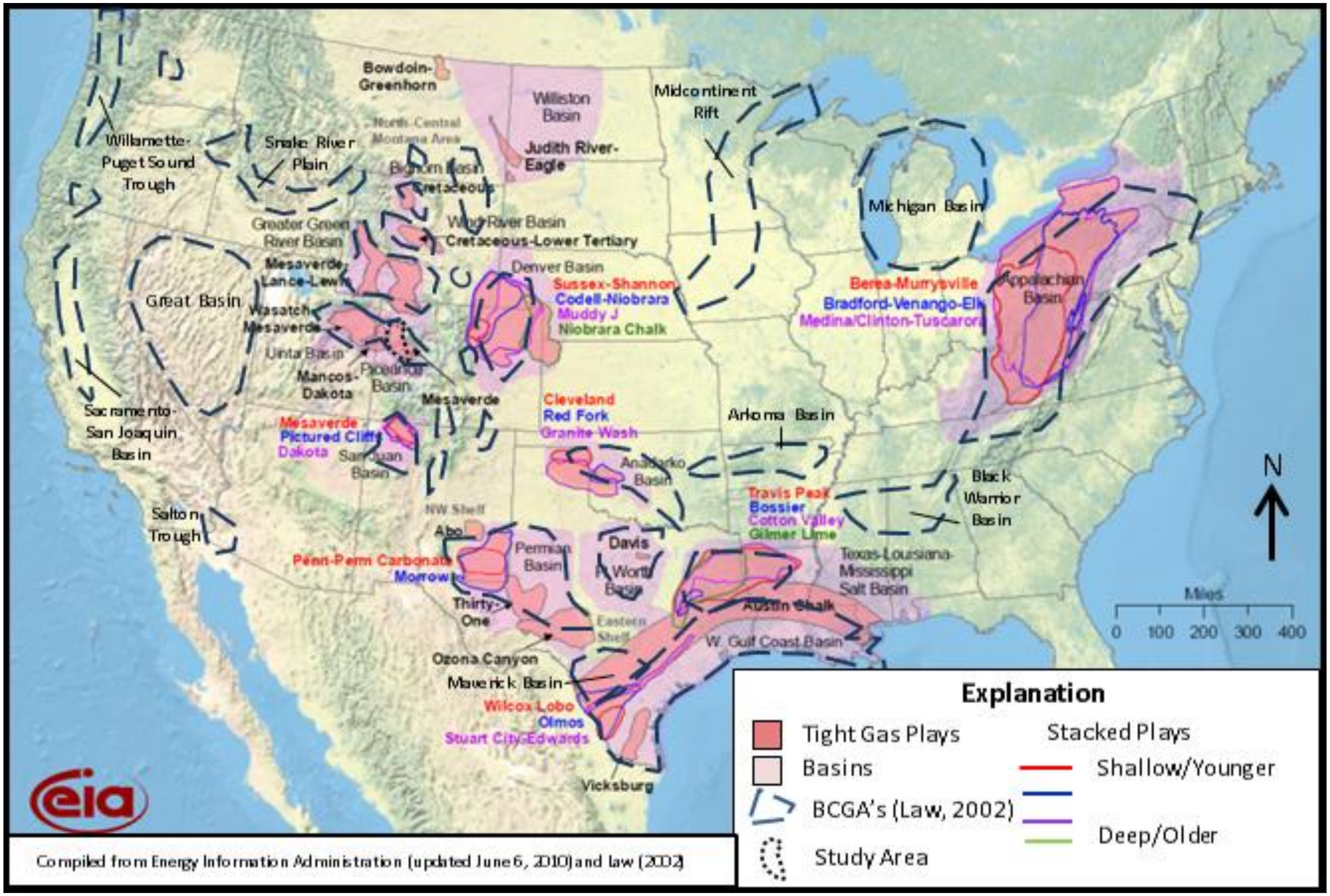
The recognition of these sequence-stratigraphic surfaces within the lower Williams Fork Formation interval from the eastern to western extent of the basin (Paonia, CO to the Utah – Colorado state line) have not been identified in previous regional studies (Johnson, 1989; Tyler and McMurray, 1995; Hettinger and Kirschbaum, 2002). Flooding surfaces are especially useful when applying sequence stratigraphy, however can be difficult to recognize especially in nonmarine successions. Previous work has documented the importance of tidal deposits recognized within nonmarine successions (flooding surface indicators) anywhere from 10 to100 km landward of paleoshorelines (Shanley and McCabe, 1994; Steel et al., 2011). The identification of tidal deposits in this study has strengthened the sequence-stratigraphic understanding through the lower Williams Fork Formation and recognized a different datum to flatten on within the Piceance Basin (as opposed to flattening below within the Mancos).

Based on previous ammonite and radiometric dating from Gill and Hail (1975) and Cobban et al. (2006), the total time duration for the deposition of this interval is estimated at1.5 Ma (75.08Ma-73.52Ma). Each depositional sequence duration represents approximately 260 ky and is classified as a high frequency +/-4 order sequence.

Thickness trends identified within sequence set A (SB 4-SB-2) show a thickening towards the northeast and thinning near the Douglas Creek Arch and minor thins in the southwest, approaching the Uncompahgre Uplift. These thin zones may provide insight into the timing and development of the DCA and UU as well as affected the depositional systems and their geographic locations. Sequence set B (SB7-SB2) shows a similar thickening direction to the northeast, however this map shows thinning in the west, southwest, and northwest part of the basin. This thinning along the western flank of the Piceance Basin could be indicative of coeval growth of these structures during deposition. These structures (DCA, UU, and/or the UMU) appear to have influenced the paleodrainages and preferential locations of incised valleys throughout the total interval. For example, relative thick zones identified in the west near the DCA and UU show corresponding thick zones in the eastern part of the basin. Statistics were run in order to compare thickness trends to net sandstone within the SB-4 to SB2, SB-7 to SB4, and total SB7-SB2 intervals. With a GR cutoff set at 95 API, net-sandstone maps show reasonable thick sandstone accumulations near current producing gas fields in the basin; however some of the producing fields do not necessarily correspond with thick sandstone accumulations.

This study integrated both outcrop and subsurface well data in order to install a regional sequence-stratigraphic framework to the lower Williams Fork Formation. The conclusions and methodology brought about from this study emphasize the importance of field observations and field data collection. This study provides key outcrop analysis within the marine to nonmarine transition and utilizes these data to correlate to nearby well logs in the subsurface. The idea is that companies exploring in the basin can use outcrop to subsurface correlation criteria compiled in this study, to apply to complete subsurface datasets and enhance stratigraphic understanding in order to better production within the Piceance.

Figure 1.1 Tight gas plays with basin locations, and basin-centered gas accumulations (BCGA's) in the lower 48 United States (Compiled from Energy Information Administration, 2010; Law, 2002).



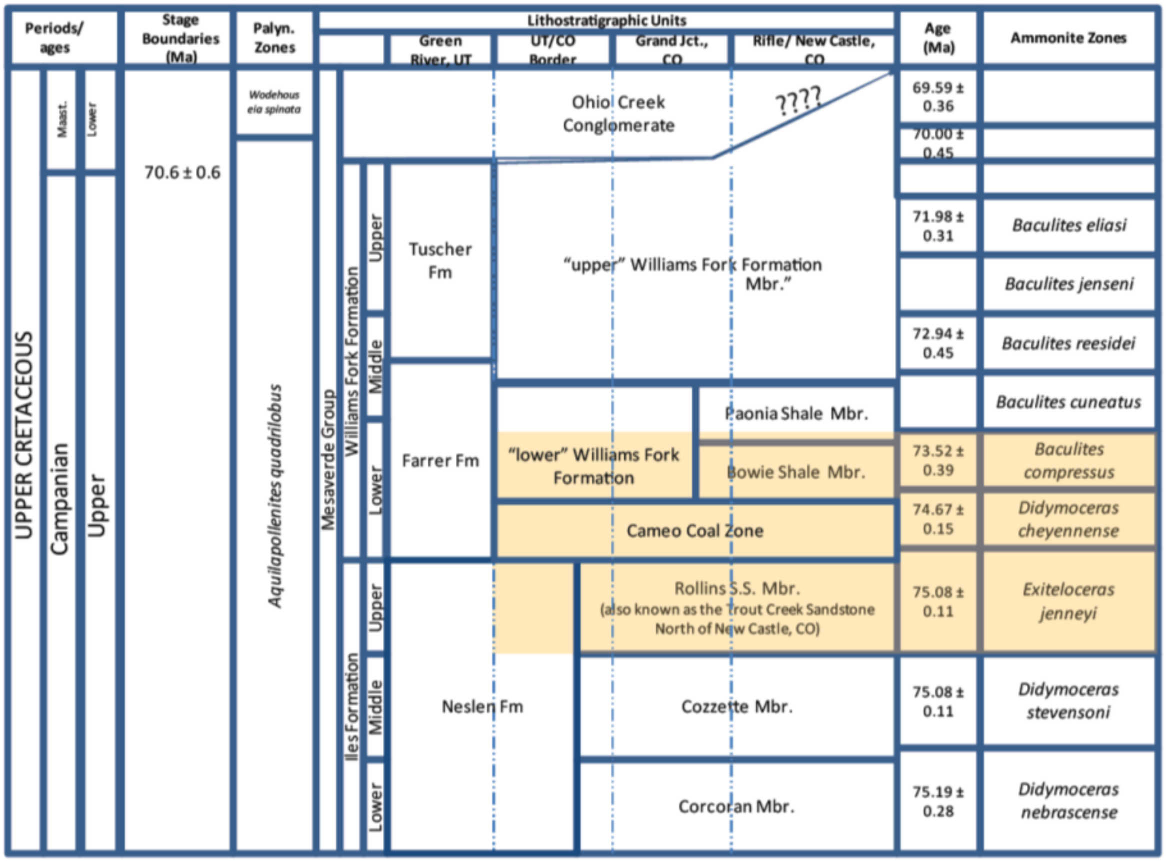


Figure 1.2 Stratigraphic nomenclature chart from eastern Utah to the eastern part of the Piceance Basin in northwestern Colorado. Correlation is not as well understood and, therefore is speculative into the Uinta Basin, in eastern Utah. Ammonite zones and radiometric dating of ashes help constrain ages in millions of years of lithostratigraphic units from the west to the east part of the basin. Compiled from Hettinger and Kirschbaum (2003), Cole and Cumella (2003), Johnson and Flores (2003), Kirschbaum and Hettinger (2004), and Cobban et al. (2006).

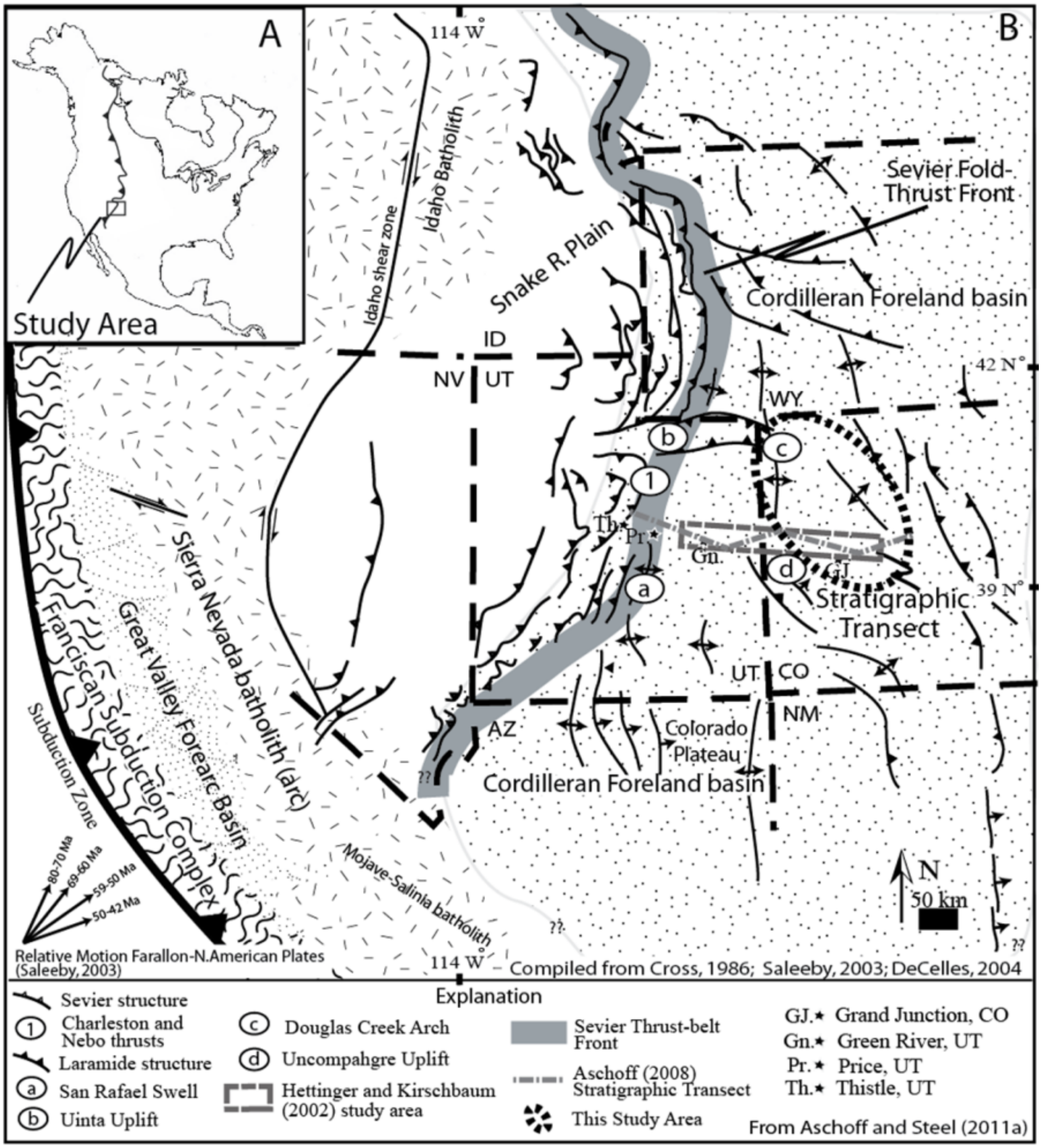


Figure 1.3 (A) Map of North America highlighting the study location in respect to the Sevier Fold-Thrust Belt. (B) Regional map of the Cordilleran Foreland Basin in Utah and Colorado. The shaded gray line represents the Sevier fold-thrust belt, located to the west of the study area which is shown as a shaded gray dashed oval. Laramide style, basement-cored structures are also identified and lettered (a to d). From Aschoff and Steel (2011a).

API	Section Name	Date	Lat	Long	Stratigraphic Units	Thickness (m)	Thickness (ft)
LitHorsDra	Little Horse Draw (LHD)	7/15/2009	39.824597	-108.840569	Rollins-lower Williams Fork	298.5	979.33
CoalCanyon	Coal Canyon (CC)	7/22/2009	39.12466	-108.37115	Rollins-lower Williams Fork	297	974.41
BigSaltCrk	Big Salt Creek (BSC)	7/25/2009	39.367752	-108.731597	Rollins-lower Williams Fork	375	1230.31
HunterCnyn	Hunter Canyon (HC)	10/4/2009	39.29231	-108.580712	Rollins-lower Williams Fork	254	833.33
EastSltCrk	East Salt Creek (ESC)	7/30/2009	39.439003	-108.786083	Rollins-lower Williams Fork	359.75	1180.28
KannhCrkLE	Kannah Creek/Lands End (KCLE)	7/28/2009	38.994732	-108.262178	Rollins-lower Williams Fork	527.7	1731.30
KennyResvr	Kenny Reservoir (KR)	5/10/2010	40.131079	-108.698384	Cozzette -lower Williams Fork	261	856.30
WhiteRiver	White River 102 (WR102)	5/15/2010	40.076174	-108.896346	Rollins-lower Williams Fork	816	2677.17
MoyerHwy13	Moyer 13 (M13)	5/19/2010	40.024025	-107.953734	Rollins-lower Williams Fork	400	1312.34
RifleGapSP	Rifle Gap State Park (RG)	5/22/2010	39.6225	-107.763197	Rollins-lower Williams Fork	510	1673.23
DevilsHole	Devils Hole (DH)	8/22/2010	40.156728	-107.954363	Rollins-lower Williams Fork	677.5	2222.77
ElkCkElmBM	Elk Creek Elementary-Burning Mountain (ECE/BM)	8/25/2010	39.570146	-107.545946	Rollins-lower Williams Fork	541	1774.93
SoCanyonCk	South Canyon Creek (SCC)	8/29/2010	39.535466	-107.420178	Cozzette-lower Williams Fork	451	1479.66
DltaGnBrd2	Delta Gunnison Border 2 (DGB2)	10/10/2010	38.929691	-107.507403	Rollins-lower Williams Fork	532.5	1747.05
NoThompCrk	North Thompson Creek (NTC)	10/11/2010	39.317383	-107.308812	Rollins-lower Williams Fork	223	731.63
RioBlncoPC	Rio Blanco-Piceance Creek Road (RBPC)	11/20/2010	39.732258	-107.935321	Rollins-lower Williams Fork	176	577.43

Table 1.1 New stratigraphic profile names and GPS latitude and longitudinal coordinates with the total thickness interval of each profile.

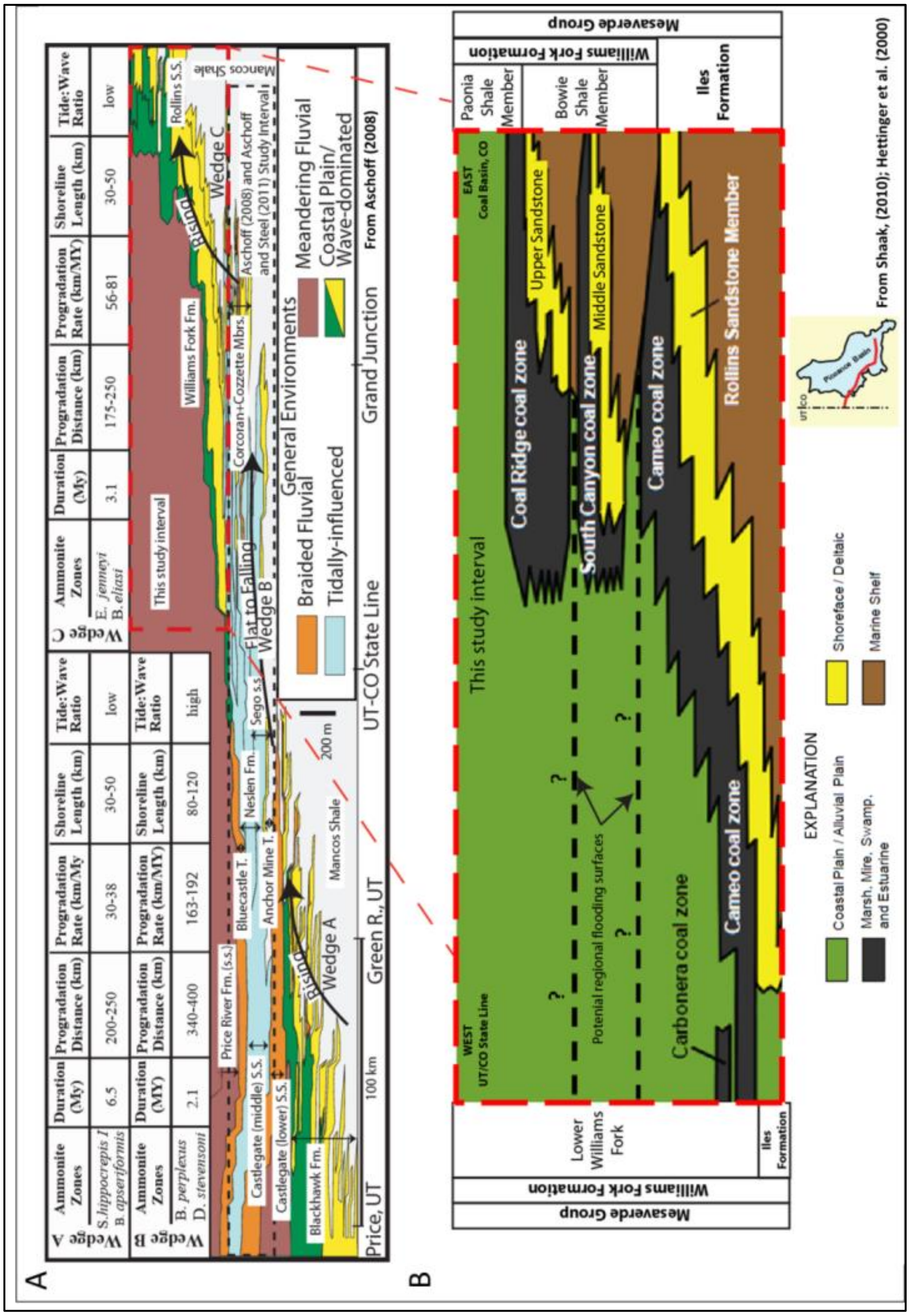


Figure 1.4 (A) West to east stratigraphic cross section with nomenclature along the BookCliffs from Utah to Colorado showing the distribution of shoreline stacking patterns within the Mesaverde Group. Modified from Aschoff, (2011a). (B)West to east stratigraphic cross section through the southern Piceance Basin which illustrates the distribution of marine shelf, shoreface/deltaic, marsh/estuarine, and coastal-plain/alluvial depositional environments. The study interval is within the upper Iles and lower Williams Fork formations (highlighted in the red box). The dashed lines with question marks represent potential regionally extensive flooding surfaces. Compiled from Shaak (2010), and Hettinger et al. (2000).

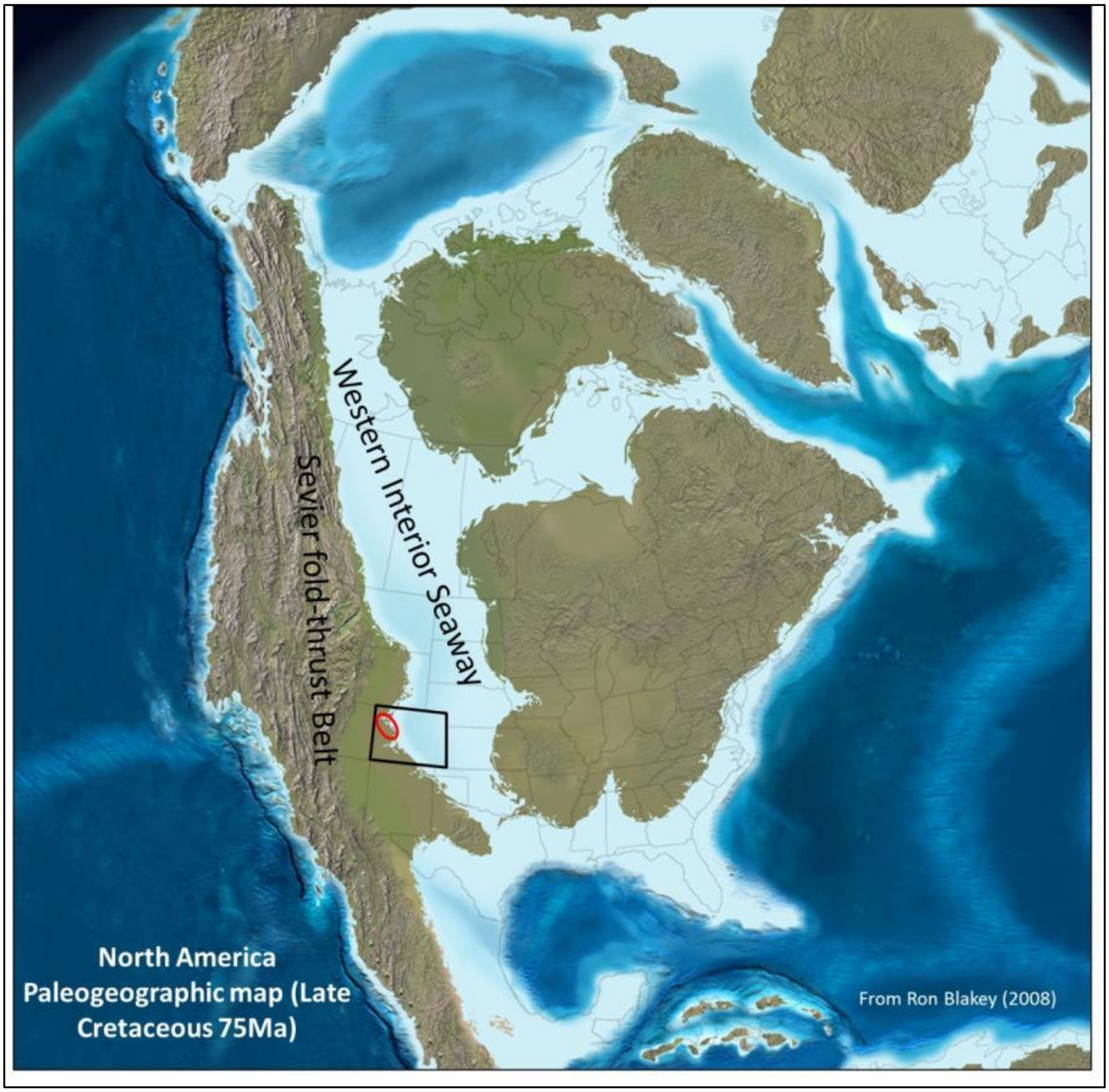


Figure 1.5 Paleogeographic map during the Late Cretaceous (75Ma) illustrating the span of the Western Interior Seaway from Canada down to the Gulf of Mexico. Colorado is outlined in a black box and the study area in a red circle. Notice the Sevier fold-thrust belt to the west of the study area. This map is from Blakey (2008b).

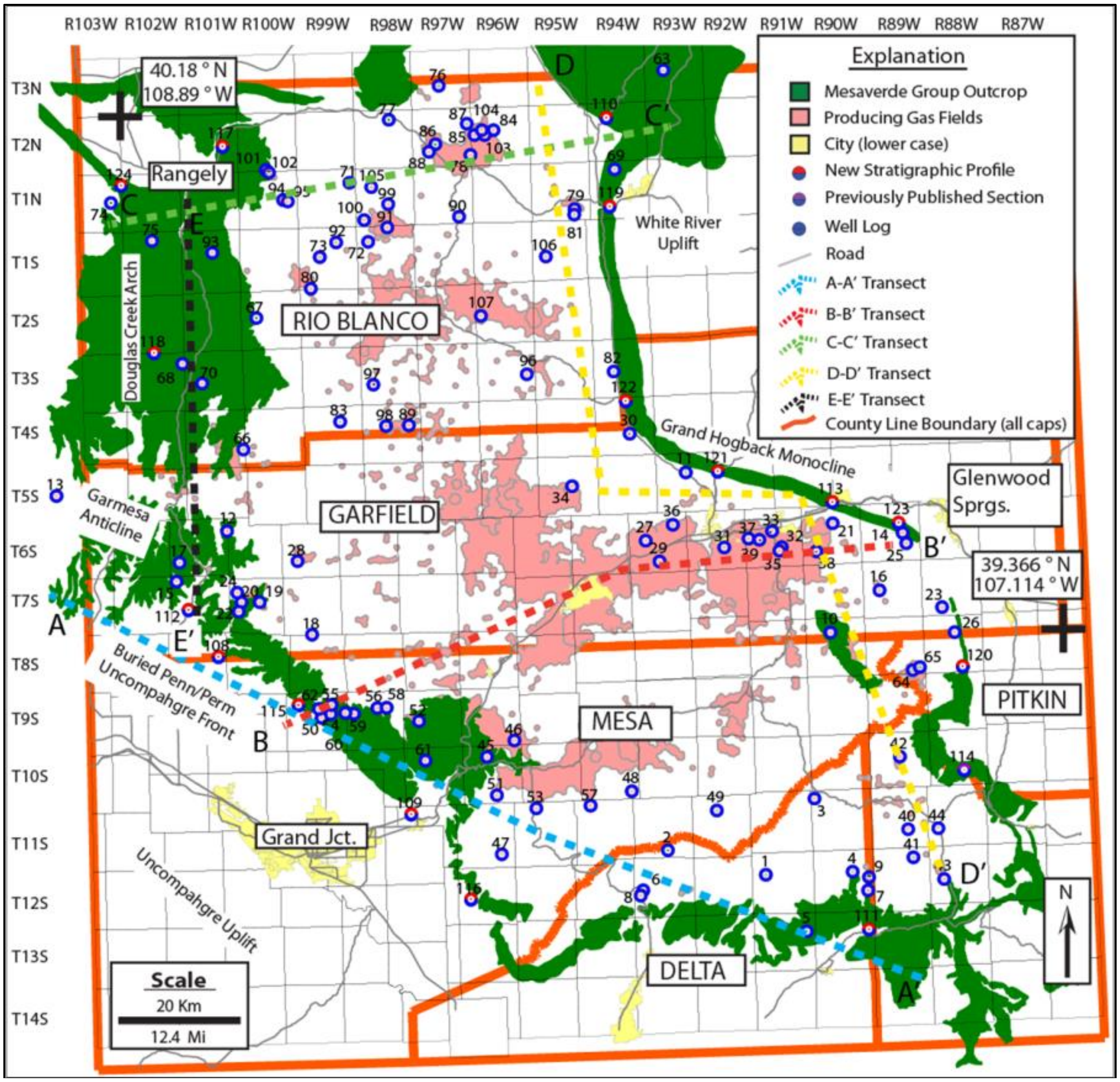


Figure 1.6 Map of the Piceance Basin located in Northwestern CO. The location of the Mesaverde Group outcrop is represented in green (Green, 1992; Tweto, 1979). Pink represents producing natural gas fields (Colorado Oil and Gas Commission, 2011). All of the data points utilized in this study are numbered and represented by the blue circles (new and previously measured stratigraphic profiles are represented by a half red and half purple circles respectively).

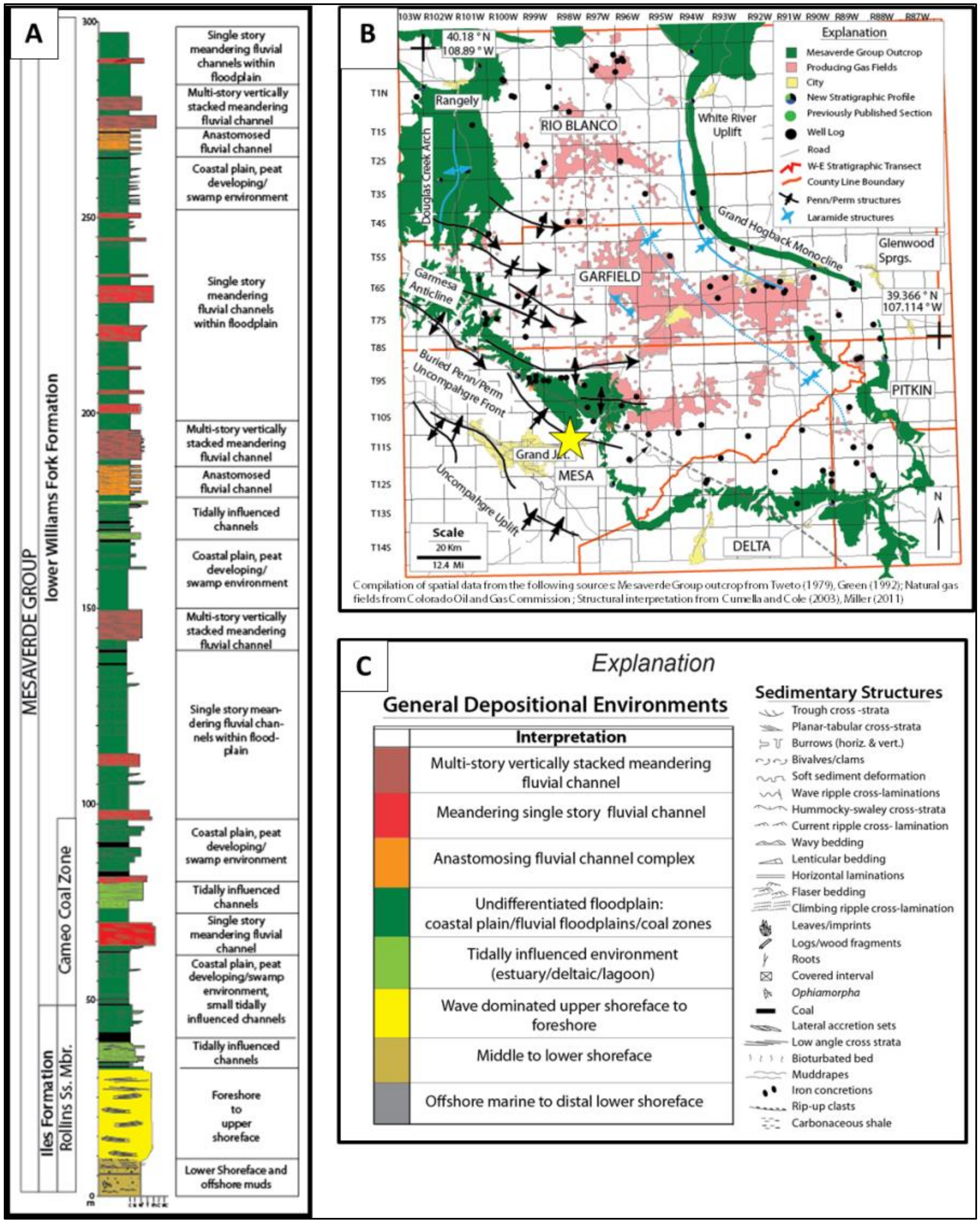


Figure 1.7 (A) Generalized stratigraphic column illustrating facies associations and stacking patterns transitioning from marine to continental fluvial deposits within the study. (B) Map of the Piceance Basin and outcropping Mesaverde Group, with the location of the measured section (yellow star) at Coal Canyon, north of Palisade, CO. (C) Explanation of the interpreted depositional environments and sedimentary structures.

Fluvial Facies Identified in Stratigraphic Sections

Facies	Description	Processes
1	Semi-continuous, flat-based, 1.5-5 m thick, dark gray-black, carbonaceous shale and siltstones, horizontally-laminated with locally structureless with locally small wood imprints/fragments	Dominantly suspension depostion, low water energy within the lower flow regime with minor traction transport, near organic rich source
2	Semi-continuous, flat-based, 0.10-8 m thick, black, coal with locally interbedded shale and minor siltstone, structureless to blocky, low density, high terrestrial organic matter, can appear vitric on fractures and cleats	Suspension settling, minor traction transport, low flow regime, low energy
3	Semi-continuous, irregular-based, 0.50-5 m thick, brown to tan, very fine- to fine-grained sandstone, trough cross-strata with superimposed current-ripple cross-laminations, can have local soft sediment deformation (SSD) and iron concreations, lateral accreation sets observed, increase in current-ripple cross-laminations interbedded with siltstone and mudstone towards the top of facies	Bimodal current directions, the main current deposited dunes, the second current of lower flow regime, deposited ripples , traction transport
4	Discontinuous, irregular-based, 0.03-0.10 m thin, lenticular sandstone body, brown-tan, very fine-grained sandstones, current-ripple cross-laminations with thin interbedded mud, well-sorted, quartz-rich sandstone	Local deposition, low flow regime, dominantly traction transport with minor suspension settling
5	Discontinuous, irregular-based, 0.50-3 m thick, tan- cream, upper very fine- to upper medium-grained sandstone, trough and planar -tabular cross-stratified sandstones, tend to see planar-tabular cross-strata towards the top of unit, can vary in mud content locally	Unidirectional, upper part of the low flow regime, traction transport
6	Semi-continuous to discontinuous, irregular-based, lenticular sandstone bodies, 1-15 m thick, tan to brown, fine- to upper fine-grained sandstone with granule to pebble size mudstone clasts concentrated at base, clasts aligned in same orientation and direction as the planar-tabular and trough cross-strata, lateral accretion sets observed, high net to gross sandstone	Unidirectional, higher flow velocities within the upper part of the low flow regime to scour/transport larger grain sizes
7	Discontinuous, irregular-based, 0.30-1.5 m thick, brown, light tan, or red, conglomerate with subangular to subrounded siltstone clasts ranging from granule to cobble size. Within a fine- to upper fine-grained sandstone matrix. Local soft sediment deformation, massive (structureless) unit, with faint normal grading, scalloped lower bounding surface	Unidirectional flow, high sedimentation rate or high flow velocities
8	Discontinuous, irregular basal and upper contact, 0.20-1.5 m thick, red-tan to light tan color, fine- to upper fine-grained, horizontally-laminated, locally high clay clast concentrations present at base as well as SSD, composition: 60% qtz, 30% feld, 10% chert, iron concretions	Unidirectional, upper flow regime structures from high sedimentation rate, or increase in sediment supply
9	Semi-continuous, irregular-base, lenticular geometry (width:10-20 m), 15 m thick, light tan to cream, fine- to medium-grained sandstone, massive (structureless), trough cross-strata with current-ripple cross-laminations interbedded with minor mud locally moving up stratigraphically, salt and pepper texture	Unidirectional flow, high flow velocities and/or high sediment fall out rates, traction transport, multiple small channels scour and fill features
10	Discontinuous, irregular-based, 0.30- 2 m thick, red-tan to brown, very fine- to fine-grained sandstone, current-ripple cross-laminations, locally interlaminated with mudstone, high concentration of calcite cement typically occurs at the top of facies.	Unidirectional flow, traction transport, low flow regime, with increase in suspension settling stratigraphically
11	Semi-continuous to discontinuous, irregular-based (can have flat-based appearance locally), 0.20- 8 m thick, gray to dark gray, ranges from clay to very fine-grained sandstone, carbonaceous mudstone interbedded with current-ripple cross-laminated to structureless siltstone and very fine-grained sandstone, 65% mud/35% sand. Increasing sandstone content stratigraphically up	Unidirectional to multi-directional flow, suspension settling, with simultaneous suspension and traction transport occuring rapidly due to flow expansion
12	Semi-continuous to discontinuous, moderately flat-based, 0.10-5 m thick, gray- green mudstone- siltstone, however sometimes a siltston to very fine-grained sandstone with relict current ripple cross-laminations, paleosol red to green patchy appearance, root traces, and sometimes small wood imprints or fragments, slickenlines also can be found locally, blocky or nodule-like fracture characteristic from weathering	Dominantly suspension settling with periods of non-deposition occuring during times of paleosol development
13	Semi-continuous to discontinuous, irregular-based, 8-10 m 1thick, cream-tan brown, medium- to upper medium-grained sandstone, trough cross-trata and changes stratigraphically to planar-tabular cross-strata towards top	Unidirectional, upper part of the low flow regime, high sediment supply
14	Laterally discontinuous, irregular-based, 0.50- 5 m thick, red to tan, very fine- to fine-grained sandstone, current-ripple cross-laminations within lateral accretion sets. Overall fining upward pattern, typically more feldspathic with increase in lithic fragments, 70-80% quartz, interbedded mud in between sandstone lateral accretion sets	Unidirectional with some multidirectional component, dominantly traction transport, decrease in flow velocity towards top of bed where suspension processes are introduced

Table 1.2 Facies identified in this study have been assigned to the fluvial tract and described and interpreted with fluvial characteristics.

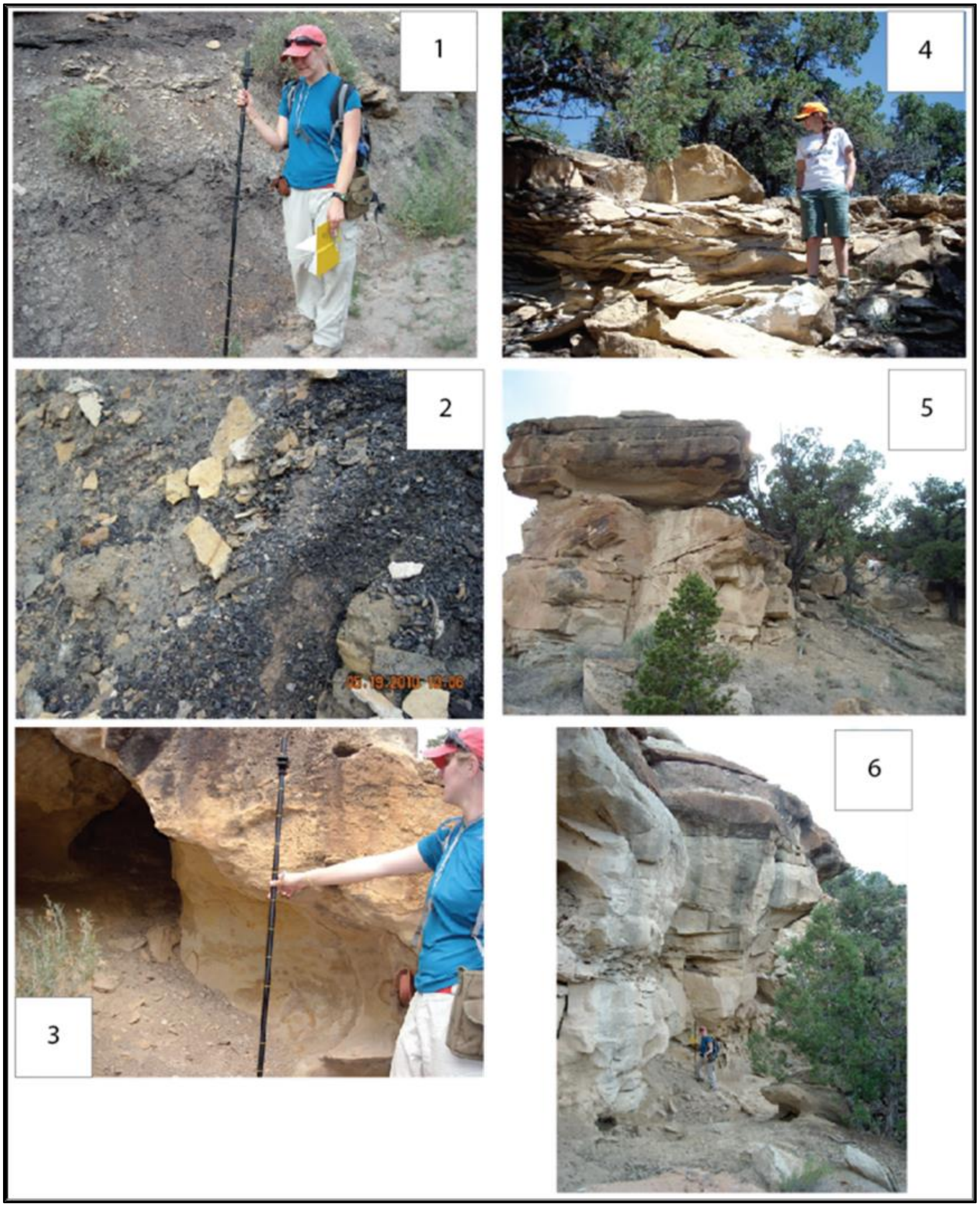


Figure 1.8 Examples of fluvial facies 1-6. (1) Organic-rich shale and siltstone (Little Horse Draw). (2) Organic rich coal (Moyer-Hwy 13). (3) Very fine to fine grained sandstone with superimposed trough cross-strata and current ripple cross laminations (Little Horse Draw). (4) Very fine grained sandstone with current ripple cross-laminations thinly interbedded with siltstone and mudstone from (Little Horse Draw). (5) Fine- to medium-grained sandstone with trough and planar tabular cross-strata at (Little Horse Draw). (6) Granule to pebble mudstone clast conglomerate at base with planar tabular and trough cross-strata above (Little Horse Draw).

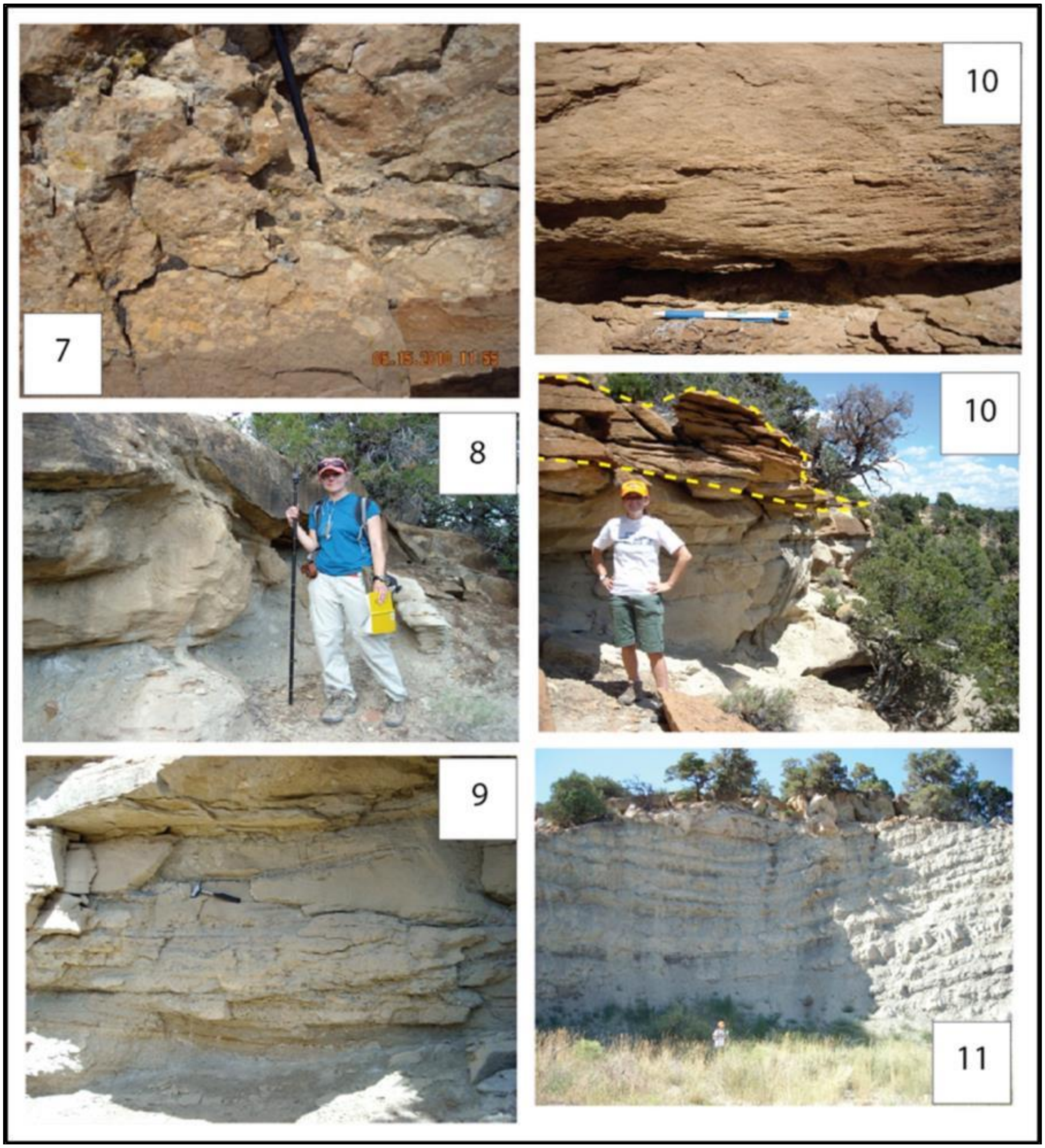


Figure 1.9 Continued examples of fluvial facies 7 through 11. (7) Red to tan granule to cobble grained conglomerate within a fine to upper fine grained sandstone matrix (White River). (8) Fine- to upper fine-grained sandstone, horizontally laminated with local soft sediment deformation (Little Horse Draw). (9) Fine- to medium-grained massive to trough cross-stratified sandstone (Little Horse Draw). (10) Very fine- to fine-grained sandstone with current ripple cross-laminations commonly cemented with calcite (Little Horse Draw). (11) Highly interbedded carbonaceous mudstones, siltstones, and current ripple cross-laminated and very fine-grained sandstone (Little Horse Draw).

Figure 1.10 Continued examples of fluvial facies 12 through 14. (12) Gray-green mudstone and siltstone with a patchy red-green paleosol appearance, root traces and can have a nodule-blocky weathering characteristics (East Salt Creek and Little Horse Draw). (13) Medium- to upper medium grained trough and planar tabular cross-stratified sandstone (East Salt Creek). (14) Very fine- to fine-grained ripple cross-laminated sandstone with lateral accretion sets (Kenny Reservoir).

Marine and Shallow Marine Facies Identified in Stratigraphic Sections

Facies	Description	Processes
15	Continuous, flat-based, 1- 180 m thick, black to dark gray shale with minor siltstone, horizontally- laminated with locally structureless interbedded siltstones , organic-rich, however, no fossils could be identified	Low energy, suspension deposition
16	Continuous, moderately flat-based, 5-10 m thick, tan to light orange/brown color, fine- to medium-grained sandstone, horizontal to low-angle strata, horizontal strata with local *Inoceramus* bivalve stratified layer (concave down) are typically observed at the base and dominantly vertical burrow structures and a low diversity and abundance of *Ophiomorpa* at the top, iron concretions can preferentially occur with *Ophiomorpa* burrows, quartz rich, well sorted (disturbed with mud and sand where burrowing is present).	High energy environment for opportunistic organisms, traction transport by waves
17	Continuous, flat-based, 1-20 m thick, white to cream "bleached" sandstone, fine- to medium-grained homogenous sandstone, trough cross-strata, minor indication of bioturbation (low abundance and low diversity of organisms *Skolithos* ichnofacies observed), clean well-sorted sandstone, 90% quartz and minor lithics/chert (10%), weathers round, honey-comb fracture pattern, 0.4-0.6 m in diameter round iron-oxide circles present at top boundary from tree roots found locally	Bidirectional, traction transport by higher energy waves (within the upper part of the lower flow regime)
18	Continuous, flat-based, 1- 10 m thick, tan- brown color, siltstone to very fine-grained sandstone with hummocky cross-strata, *Cruziana* ichnofacies such as *Thalassinoides* (lower) and *Ophiamorpha* (top) trace fossils observed	Fluctuating high and low bidirectional current energy, with the high energy lasting a short time, storm waves, moderate diversity, low abundance
19	Semi-continuous to continuous, flat-based, 0.20-1 m thick, creamy tan to a brown, very fine- to medium-grained sandstone, structure-less, high bioturbation, however, no organisms could be identified, highly heterolithic mud and quartz sand grains	Suitable conditions for organisms to survive (high abundance and/or high diversity or low diversity), fluctu-ating between traction transport (dominant process) and suspension settling
20	Continuous, flat-based, 0.50-3 m thick, tan to gray, clay to very fine-grained sand sizes (clay tends to weather out), wave ripples interbedded with horizontally-laminated carbonaceous shale where sedimentary structures are preserved, possible biogenic traces of *Thalassinoides* or horizontal burrowing, low diversity, *Diplocraterion* also observed	Bidirectional, intermixed traction transport with suspen-sion settling, moderate to high energy based on traces preserved
21	Semi- continuous to continuous, flat-based, 0.20-2 m thick, creamy tan to gray-brown, clay to fine-grained sandstone, bioturbated, structureless and heterolithic mud and sand. *Inoceramus* stratified layer, oriented concave down, typically found at the base of a bed, *Inoceramus* bivalves can range in size from 2 cm to 30 cm. Many *Cruziana* and *Skolithos* ichnofacies were identified. Top of bed: *Rhizocorrallium*, *Arenicolites*, and *Planolites*, Bottom of bed: *Inocermus* bivalves, and *Asterosoma*, and *Asteriacites*	Bidirectional flow, very high diversity, high abundance of traces and fossils, low preservation of sedimentary structures from high organism activity, moderate energies and traction transport
22	Semi-continuous to continuous, moderately flat-based, 0.10-5 m thick, tan to cream color upper fine- grained sandstone, trough cross-strata with some bidirectional planar-tabular cross-strata, high concentration of small bivalve/shell fragments in the lower 2 meters of the facies	Bidirectional, moderate sedimentation rates, moderate to high wave energy
23	Continuous, moderate to flat-based, 0.50-5 m thick, tan to cream, upper fine- to medium-grained sandstone, with low-angle cross-stratification to swaley cross-stratification with little to no evidence of bioturbation	Moderate to high wave energy based on sand grain sizes and lack of trace fossils, mixed bidirectional rapid traction transport with minor suspension settling
24	Continuous, moderately scalloped to flat-based, 5 to 10 m thick, tan, medium-grained sandstone with massive (structureless) to low-angle cross-strata, current-ripple cross stratification towards the top, well-sorted sandstone, unusal horse-shoe shape load casts or possible trace fossil(?) which range in diameter from 2 cm to 30 cm	High wave energy, erosive/scouring surface (load casts?), bidirectional traction transport, with decreasing wave energy stratigraphically due to decrease in grain size
25	Semi-continuous to continuous, flat-based, 0.20-1 m thick, white to tan, very fine- to fine-grained, well-sorted low angle to hummocky cross- stratified sandstone, *Chondrites* can be indentified at the top of facies bed with many branching tunnles which do not inter-penetrate	Bidirectional, mixed traction transport (rapid) and suspension settling (minor), low oxygen conditions
26	Continuous, flat-based, 0.50-1.5 m thick, red-tan to white - cream, very fine- to upper very fine-grained sandstone, current-ripple cross-laminations with climbing ripples preserved locally, water escape structures, *Conichnus* trace fossil, part of the *Skolithos* ichnofacies, burrows form chevrons or v-form laminae in unit	Unidirectiona flow (possibly bidirectional, not preserved), high energy and rapid sedimentation rate based on vertical burrows and climbing ripples, dominately traction transport, minor suspension settling

Table 1.3 Described and interpreted facies identified in this study assigned to shallow marine and marine settings tract.

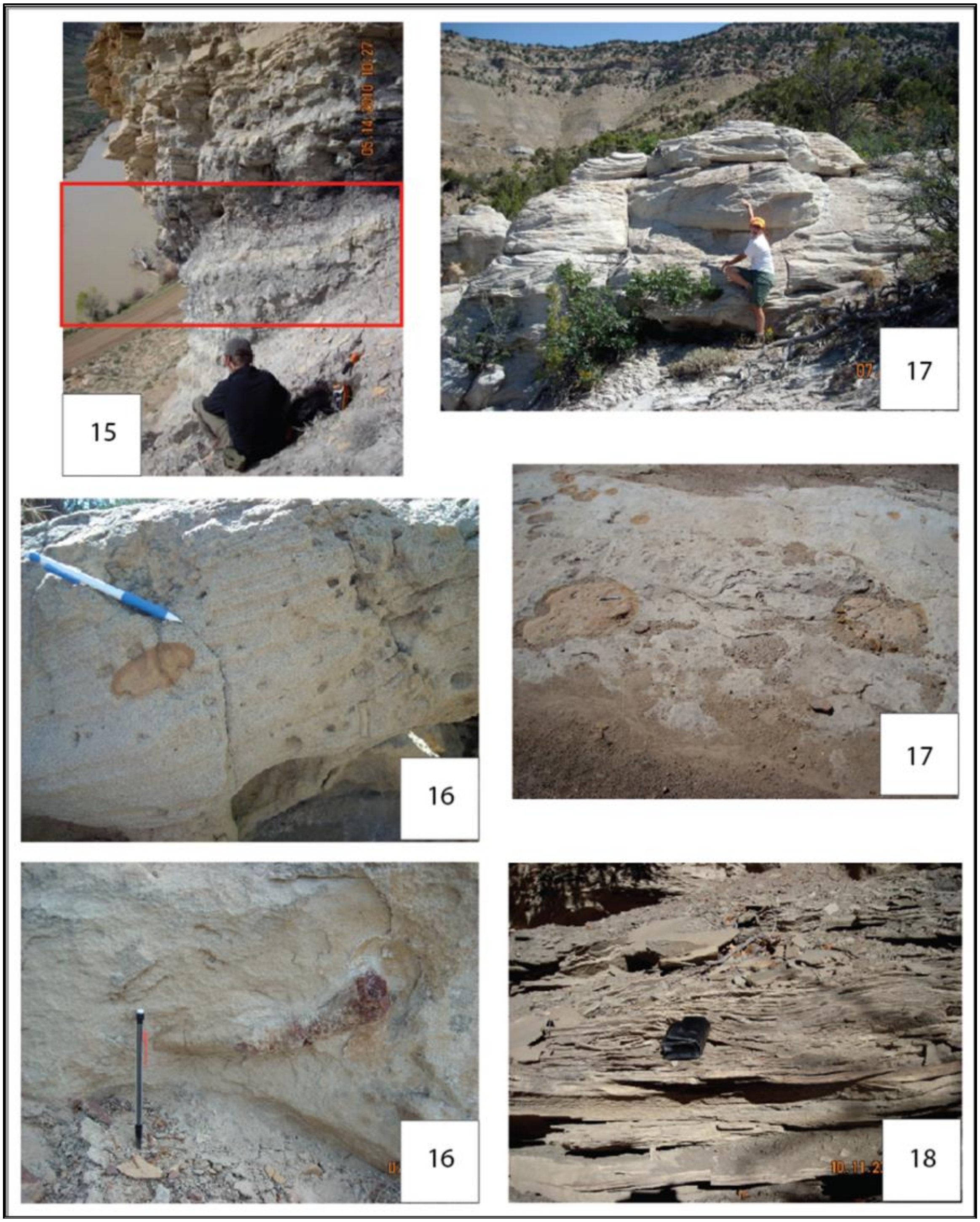


Figure 1.11 Examples of marine facies 15-18 with location of section in parenthesis. (15) Organic-rich, structureless to horizontally laminated shale and siltstones (White River). (16) Fine-medium grained horizontal to low angle stratified sandstone with vertical and *Ophiomorhpa* burrows (Coal Canyon and Kannah Creek/Lands End). (17) White "bleached" color, fine- to medium-grained sandstone with trough strata which can have round oxidized features on the top (Kannah Creek/Lands End and Coal Canyon). (18) Silt to fine-grained hummocky cross-strata (North Thompson Creek).

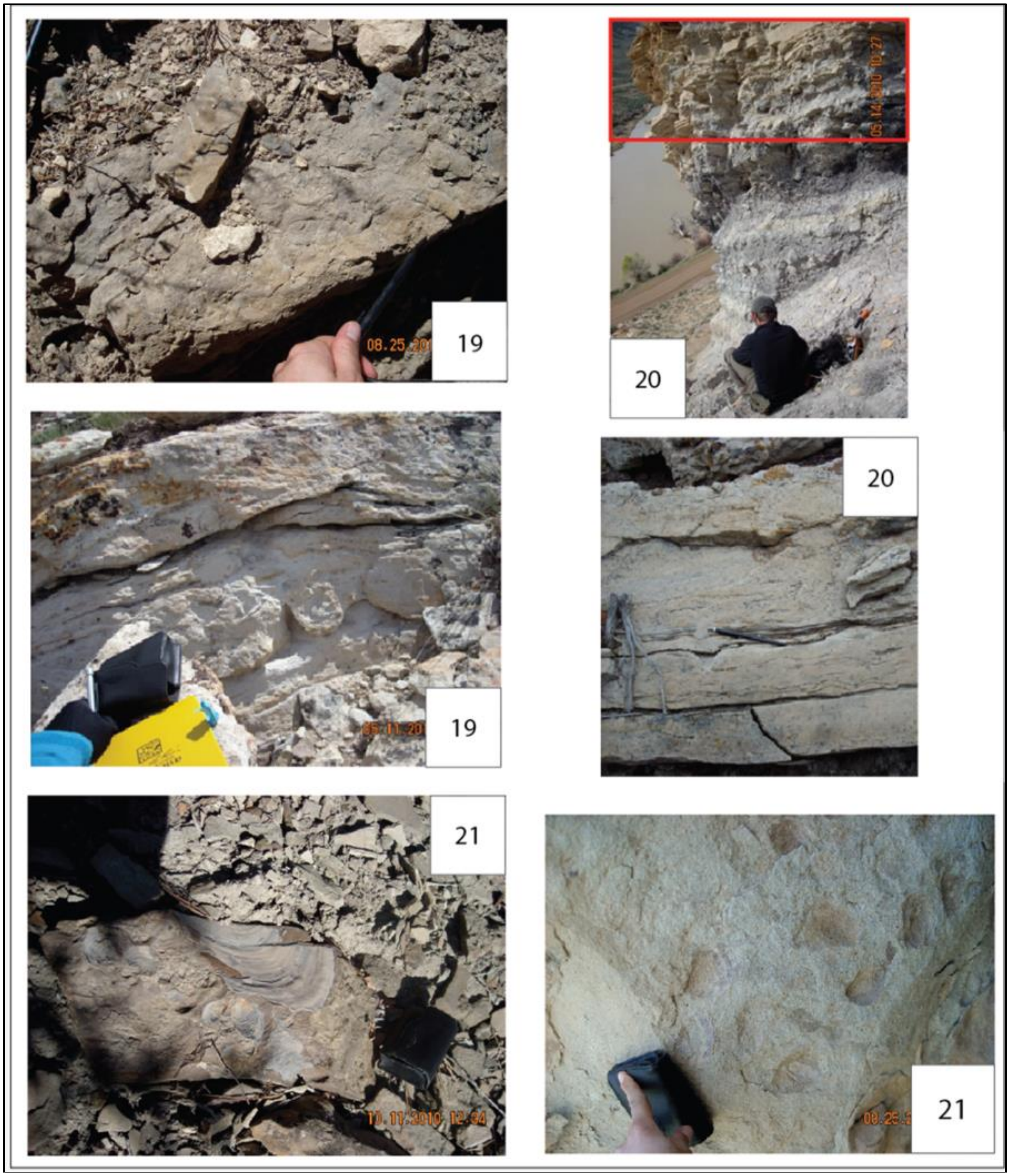


Figure 1.12 Continued marine lithofacies from 19-21. (19) Very fine- to medium-grained highly bioturbated structureless sandstone (North Thompson Creek). (20) Wave-ripples interbedded with carbonaceous shale (White River). (21) High trace fossils and organism activity and *Inoceramus* bivalves (North Thompson Creek and Elk Creek Elementary-Burning Mtn).

Figure 1.13 Continued marine lithofacies from 22-26. (22) Upper fine-grained trough to planar tabular cross-stratified sandstone with shell fragments (Delta-Gunnison Border). (23) Low angle to swaley cross-stratification (Elk Creek Elementary-Burning Mtn). (24) Sandstone with horse-shoe-shaped load casts varying in size (North Thompson Creek). (25) Hummocky cross-stratified sandstone with branching tunnels of *Chondrites* (Kenny Reservoir and Big Salt Creek). (26) *Conichnus* burrows (East Salt Creek).

Table 1.4 Described and interpreted lithofacies identified in this study which are in tidally-influenced tract.

Tidal Facies Identified in Stratigraphic Sections

Facies	Description	Processes
27	Continuous, irregular-based, 0.10-1 m thick, tan to red, clay to very fine-grained sandstone, structureless, chaotic distribution of clams, gastropods, shale clasts, and wood fragments, with local soft sediment deformation	Unidirectional flow, lower water energy, allowing for suspensions grains to settle, rapid and caotic deposition, proximal to terigenous source
28	Semi-continuous to discontinuous, moderate to flat-based, 0.50- 5 m, tan to red, clay and silt to very fine-grained sandstone, inclined heterolithic strata dipping between 10-15 degrees, with interbedded organic rich mud drapes across entire sand packages, can also occur in "clinker" burnt coal zone	Bidirectional flow, moderate to low mixed energies, high terrestrial organic matter, alternating suspension settling with upper flow regime traction transport
29	Semi-continuous to continuous, 0.20-1 m, thick, white or red, very fine- to fine-grained sandstone, structureless with local relict bidirectional current-ripple cross-laminations, high bioturbation, *Diplocriterion,* and *Glossifungities* traces preserved	Bidirectional flow, moderately high energies, moderate to suitable conditions for organizms to survive
30	Semi-continuous to continuous, flat-based, 1-5 m thick, alternating tans and grays, clay to very fine-grained sandstone, flaser/wavy/lenticular bedded with interbedded muddrapes, can show a fining or coarsening upward trend due to increase or decrease in mud content	Bidirectional currents, traction transport, mud deposited in suspension, low flow regime
31	Semi-continuous to discontiuous, 0.10-0.50 m thick, white or tan-brown, upper fine-grained sandstone, sigmoidal cross beds separated by mud drapes, quartz-rich sandstone, mud drapes typically eroded out	Unidirectional (possible that bidirectional cross strata were not preserved), moderate to low energy, both traction transport and suspenion settling
32	Continuous, flat-based, brown orange color, also appear yellow/red/gray/black, clay to very fine-grained sandstone, structureless coal, mudstone, and siltstones with interbedded sandstones, leaf and pine cone imprints and slicken lines found locally. *Teredolites* (elongate cyclindrical burrows into a wood substrate) burrows preserved, found within contorted to lenticular shaped sandstone body	Bidirectional flow, low energy environment to higher energy , past burning of coals has caused distortion of outcrop
33	Semi-continuous, flat-based, 0.20-10 m thick, alternating green-gray and orange, clay to upper very fine-grained sandstone, structureless siltstone and shales locally interbedded with upper very fine-grained horizontally-laminated sandstone (less than 5 cm thick), typically have high gamma ray responses, minor bioturbation, possibly *Planolites?* found on top of bed , minor shell fragments (small bivalves?) or root traces	Unidirectional?, low energy, dominately suspension settling with very minor traction transport
34	Semi-continuous, moderately flat based, 0.10- 1 m thick, white to gray fine- to upper fine-grained sandstone, climbing ripple cross laminations with interbedded mud drapes, lenticular sandstone bodies, minor to no bioturbation observed	Unidirectional flow (possibly bidirectional?), high sedimentation rates, high energy due to sedimentary structures, lack of trace fossils (too stressed), and grain size, dominantly traction transport with minor suspension settling

Figure 1.14 Tidal facies examples 27-30. (27) Chaotic distribution of clams and gastropod fragments (Hunter Canyon). (28) Inclined heterolithic strata (Little Horse Draw and South Canyon Creek). (29) Structureless sandstone with *Diplocriteron* burrows (Hunter Canyon). (30) Flaser, wavy, and lenticular bedding (Coal Canyon).

Figure 1.15 Continued tidal facies examples from 31-34. (31) Sigmoidal cross-bedded (Elk Creek Elementary-Burning Mtn). (32) Structureless sandstone with *Teredolites*, pine cone imprints, flat horizontal bedding typcially found in the "clinker," burnt coal zones (Moyer- HWY 13 and Rio Blanco-Piceance Creek). (33) Structureless interbedded mudstone and siltstone with bivalve shells, Planolites (East Salt Creek, Delta-Gunnison Border, and South Canyon Creek).

Table 1.5 Descriptions and interpretations of facies associations identified in this study, which have also been assigned next to the stratigraphic profiles.

Facies Associations Identified in Stratigraphic Sections		
Symbol	Description	Interpretation
A	Semi- countinuous, irregular-based units, 1to >20 m thick, tan to light gray, thinly bedded fine-grained, current ripple cross-laminated sandstone (3-10 cm). Locally interbedded with structureless, sometimes rooted mudstones. Coarse sand to conglomeratic near base of scalloped lenticular sandstone bodies. Typically has a fining up trend however, can have a blocky stacking pattern. Lateral accretion sets preserved, with cross-trough and planar-tabular strata. Near the base, cross strata can be interbedded with a high clay clast concentration, oriented in the same direction at the dune current direction. Composed of facies: 4, 5, 6, 7, 8, 9, 10, 12.	Multi-story vertically stacked meandering fluvial channel complex, main channel migration pathway with intense scour - fill features, minor flood plain influence
B	Discontinuous, irregular-based, 1 - 10 m thick, tan/reddish tan to light gray lenticular-shaped beds with trough cross-stratified with superimposed ripple cross-laminated very fine to fine grain sandstone. Has an overall fining up grainsize trend, lateral accretion sets present, locally contains soft sediment deformation including dish-pillar structures. Composed of facies: 1,2,3, 4, 5, 8, 10, 12, 14.	Single story meandering fluvial channel, high suspension load floodplain/overbank deposits, small chute/single story channels
C	Discontinuous to semi-continuous, irregular-based, large (4-12 m thick) lenticular-shaped, typically scalloped surface at the base, fine- to medium-grained sandstone. High clay clast concentration and woody fragments near the base of scalloped surfaces, along with planar-tabular cross-strata, which caps this unit. Typically has thick (1-5 m) interbed-ded clay and silt to very fine-grained sandstone packages. Clay and siltstones typically have high root traces/woody debris. The laterally discontinuous, very fine-grained sandstone lenses are thin (5-30cm) with current-ripple laminations to structureless sandstones which show overall coarsening up packages. Composed of facies: 1,2,4, 6, 8, 11, 12, 13.	Anastomosing fluvial channel, with suspended floodplain/ crevasse splay deposits and thin chute channel deposits
D	Semi-continuous, flat-based, organic rich, 0.5-20 m thick, black to dark gray shale, mudstones, and siltstones with structureless to horizontal laminations deposited in suspension, carbonaceous shales and mudstones with locally interbedded coals (0.10-1m). Root traces, woody/plant material and paleosols are commonly found. Darker green indicates coal. Composed of facies: 1, 2, 11, 12.	Undifferentiated floodplain: coastal plain and fluvial floodplains with high concentrations of suspended sediment, and coal zones. and soil development
E	Semi-continuous, flat-based with locally irregular based beds, 1-50 m, can be red, tan , or white in color, very fine-fine grained sandstone, flaser-wavy-lenticular bedding with muddrapes and few bidirectional current ripples preserved locally. Structureless and climbing ripple sedimentary structures can also be preserved in some locations. Variable ranges of abundance and diversity of clams, gastropods, *Cruziana*, and *Diplocriterion*, *Glossifungites?*. Composed of facies: 1,22, 27, 28, 29, 30, 31, 33, 34.	Tidally influenced channels in an estuary or deltaic environment, nearby swamps, stressed environment from varied salinities, protected to unproected lagoon with wash-over deposits
F	Semi-continuous, flat-based, 5-25m thick, tan to white with dark gray and black interbedded, very fine to fine grained sandstone, wavey/flaser bedded with higher presence of muddrapes, with bidirectional planar tabular and trough cross strata with relict ripple cross lamination locally. *Skolithos* and *Cruziana* trace fossils preserved locally. Typically showing overall coarsening up pattern and dominately higher net-sandsandstone ratio. Composed of facies: 22, 23, 30, 31, 32.	Tide influenced bayhead delta, estuarine, typically associated with high bioturburation
G	Continuous, flat-based, 3-40m thick, light tan-white, horizontally-laminated and planar-tabular cross-bedded, fine-medium grained well -sorted sandstonesandstone, load cast seen locally. *Inoceramus* bivalves can be found at base of of facies. Shell fragments can be found within cross stratified units. Composed of facies: 16, 17, 22, 24.	Wave dominated upper shoreface to foreshore
H	Continuous, flat-based, 2-15m, light tan-brown, very fine-grained sandstone with hummocky cross stratifrication (HCS) to a slightly coarser fine grained sandstone with low angle to swaley cross stratifiation (SCS). Pervasive bioturbation commonly with *Ophiamorpha* burrows. Composed of facies: 18, 19, 20, 21, 23, 25, 26.	Mostly middle shoreface with lower shoreface
I	Continuous, flat-based, 1-180m, black to dark gray, fissile shale, interbedded with silt and/or very fine-grained horizontal to symmetrical wave ripple laminated sandstone. Composed of facies: 15, minor 18, 19.	Predominately lower shoreface with offshore marine

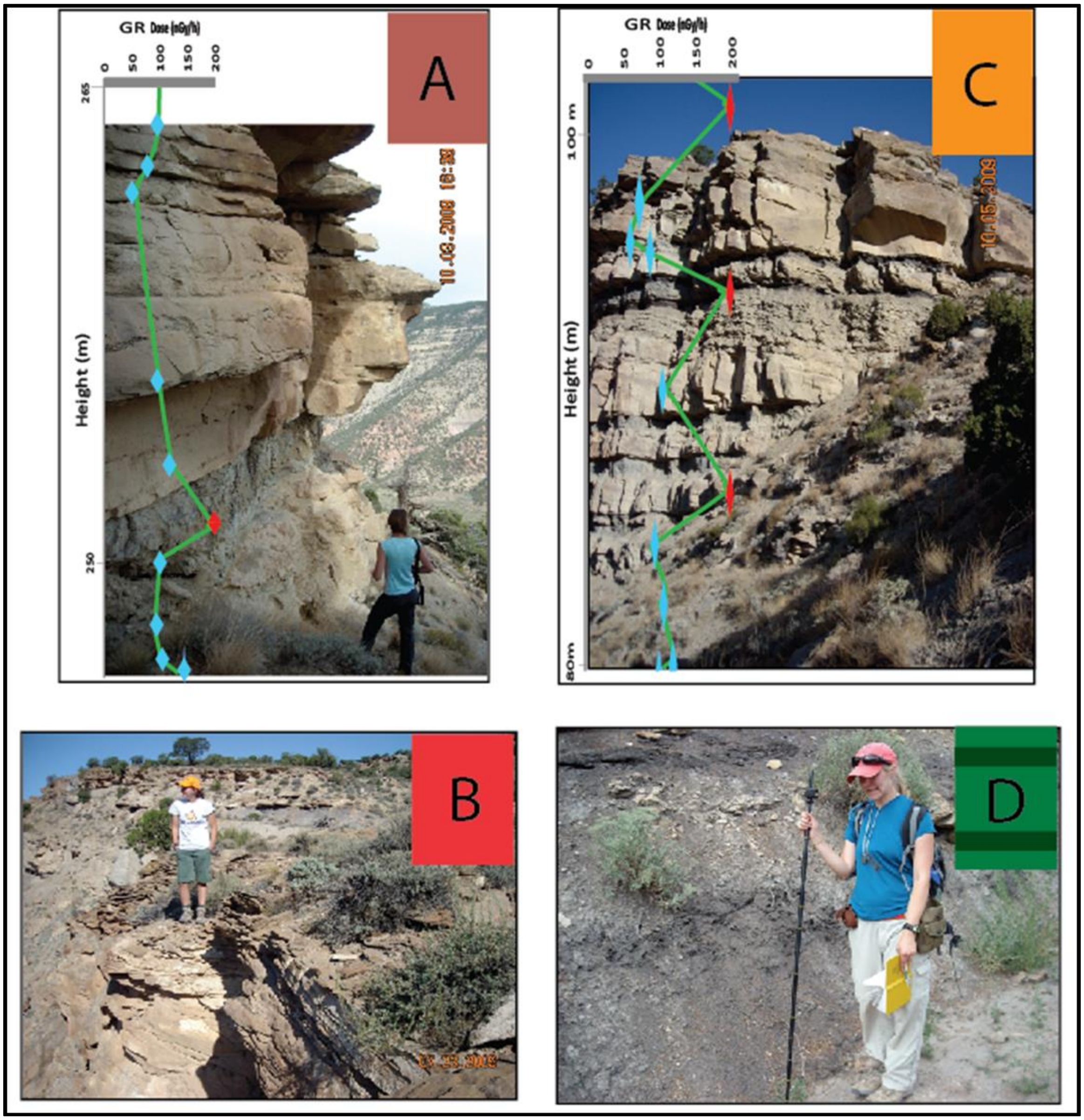


Figure 1.16 Facies associations examples of associations A through D (fluvial to undifferentiated floodplain). (A) Photo showing basal scours of the multistory vertically-stacked meandering fluvial complex overlying undifferentiated flood plain deposits at East Salt Creek (near Mack, CO). (B) Lateral accretion sets in a single-story meandering channel with high mud concentrations at Coal Canyon (Palisade, CO). (C) Shows high crevasse splay preservation and large scouring channel capping this anastomosed fluvial complex at Hunter Canyon (Fruita, CO). (D) Undifferentiated floodplain mud, varying high and/or low organic content at Little Horse Draw (Douglas Creek Arch along Highway 139). Descriptions of facies associations are listed in Table 1.5.

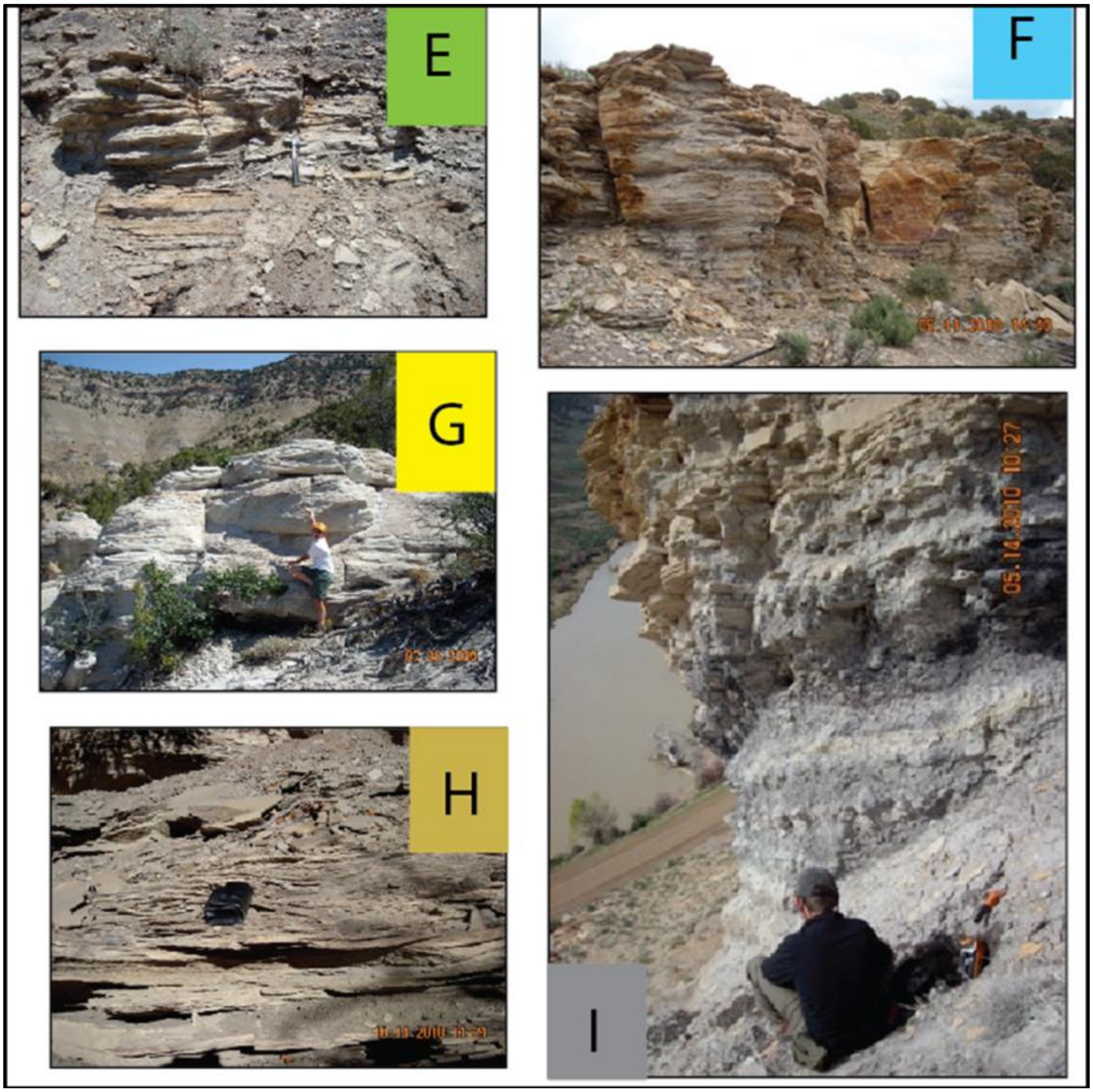


Figure 1.17 Continued facies associations examples E through I (tidally-influenced facies though offshore marine). (E) Tidally-influenced channels at Coal Canyon (Palisade, CO). (F) Tide influenced bayhead delta at Kenny Reservoir (Rangely, CO). (G) Wave dominated upper shoreface to foreshore deposits at Kannah Creek/Lands End (off Hwy 50, western side of the Grand Mesa, CO). (H) Middle to lower shoreface, hummocky-swaley deposits at North Thompson Creek (near Carbondale, CO). (I) Offshore marine to distal lower shoreface at White River (Rangely, CO). Descriptions of facies associations are listed in Table 1.5.

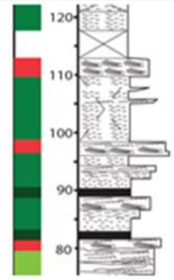
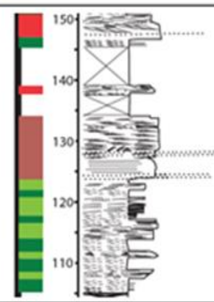
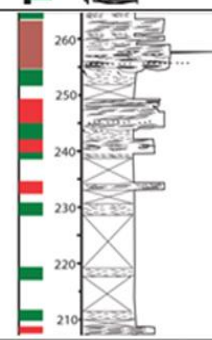
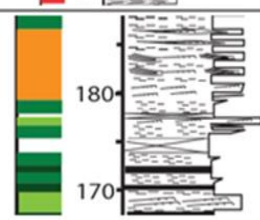
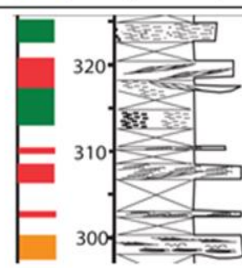
Cycle	Depositional Environment-Cycles	Outcrop Example
A	Tidal/coastal plain to single-story meandering fluvial/undifferentiated floodplain (50ft-300ft)	
B	Tidal/coastal plain to vertically-stack meandering fluvial (30-100ft)	
C	Single-story meandering/undifferentiated floodplain to vertically-stacked meandering fluvial (75-250ft)	
D	Tidal/coastal plain to anastomosed fluvial (50-100ft)	
E	Anastomosed fluvial to single-story meandering fluvial/undifferentiated floodplain (50-200 ft)	

Table 1.6 Defined fluvial cycles with interpreted depositional environments and thickness intervals. This table also shows drafted examples of the corresponding cycles from the stratigraphic profiles.

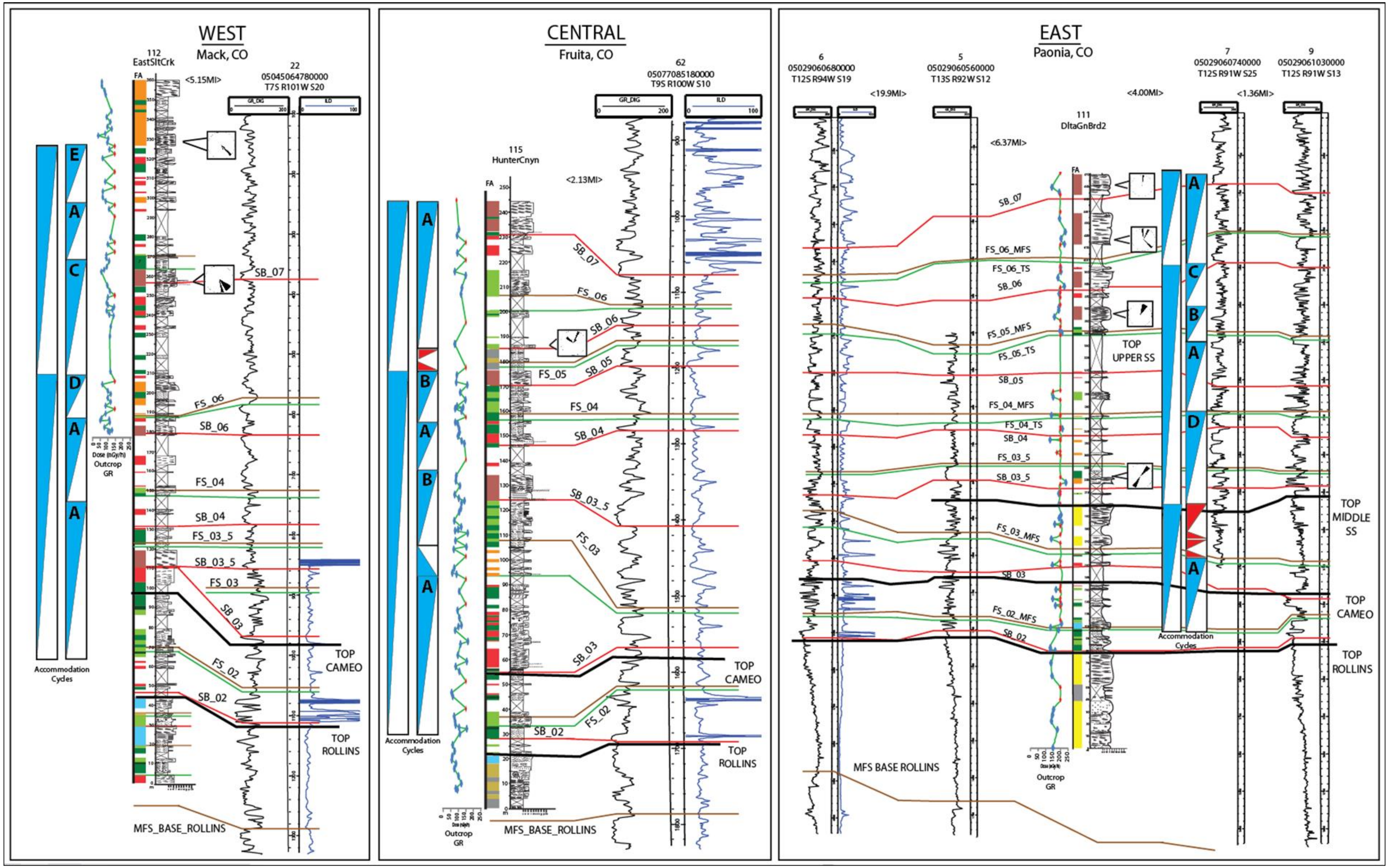


Figure 1.18 Stratigraphic profiles and type well logs showing key stratigraphic surfaces, facies stacking patterns, and accommodation cycles in relation to the western, central, and eastern parts of the Piceance Basin.

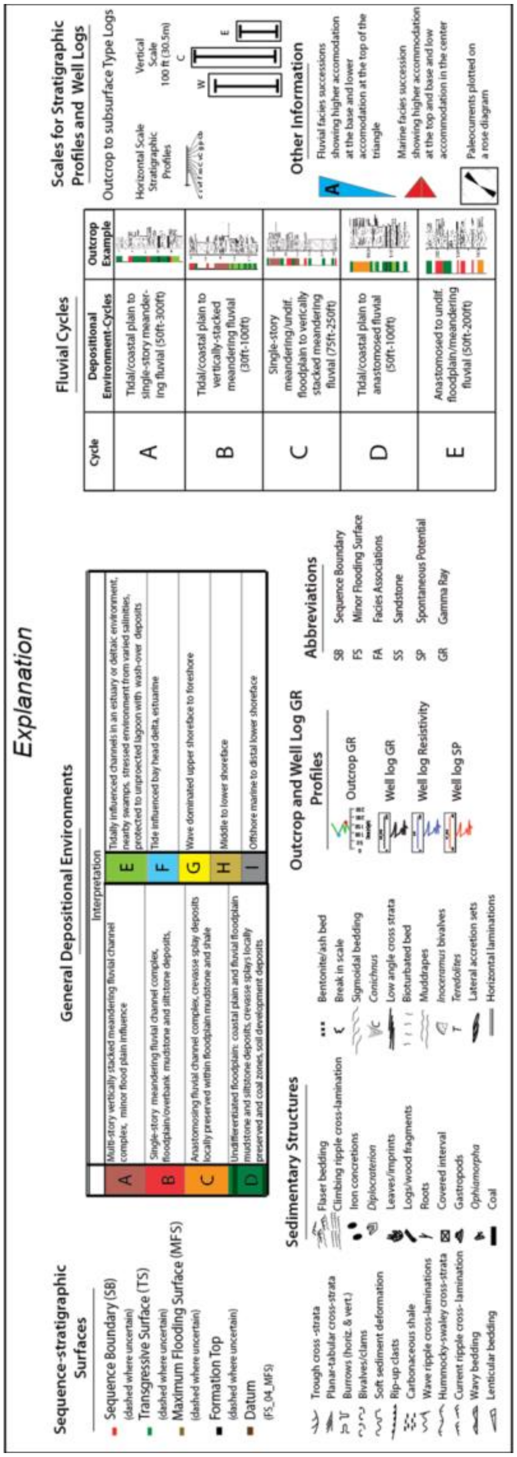


Figure 1.19 Explantion of the depositional environments, sequence-stratigraphic surfaces, sedimentary structures,and fluvial cycles identified in stratigraphic profiles and well logs utilized in this study. Abreviations, well-log scales, and horizontal and vertical scales from the type-log sections in Figure 1.12 are also explained.

Surface name	Key features for identification of surfaces
Maximum Flooding Surface Base Rollins/Top Cozzette (MFS_B-RL_T-CZ)	This flooding surface is marked by a high GR spike at the base of the coarsening up package of the Rollins Sandstone, typically found above the sharp top marine Cozzette Sandstone Member, found at the base of a thick shale package in the eastern basin, which shifts to coastal plain/tidally influenced facies overlying-more continental fluvial facies in the western and northwestern part of the basin.
Sequence Boundary 2 (SB_02)	This sequence boundary marks the first basinward shift above the sharp top of the Rollins Sandstone (a coarsening up, sharp top, marine package), with a low GR and very high resistivity curve, terrestrial organic rich coal package overlies a coarsening up, sharp top marine sandstone.
Flooding Surface 2 (FS_02)	Transgressive Surface (TS): Marks the first onset of transgression and a landward shift in facies, typically with a high GR with a low GR response below, found above the SB_ 2. Maximum Flooding Surface (MFS): Marked by the highest GR above FS_2_TS, within or having an overall serated, coarsening up pattern with a sharp top above.
Sequence Boundary 3 (SB_03)	Sequence boundary 3 is found above flooding surfaces and sequence boundary 2, basinward shift in facies more coal-undifferentiated floodplains overlying more tidal facies, or meandering fluvial overlying marine facies, picked at the base of a low GR and high resistivity.
Flooding Surface 3 (FS_03)	Transgressive Surface (TS): Marked at the base of a smooth coarsening up pattern with a sharp top, marine sandstone package on a high GR response. Maximum Flooding Surface (MFS): Chosen at the most marine, landward shift in facies, and the highest GR response in the east, chosen in between a tidal influenced-coastal plain-coaly facies in the central basin, marked by a high GR in the west within undifferentiated floodplain and single-story meandering fluvial (thin fining up packages).
Sequence Boundary 3_5 (SB_3_5)	Basinward shift in facies marked at the base of a fining up - blocky stacking pattern of fluvial facies in the central, west and northern parts of the basin. In the southeast, this surface is marked at the base of low GR and high RES coal-undifferentiated floodplain depostis directly overlying more marine, coarsening up package.
Flooding Surface 3_5 (FS_3_5)	Transgressive Surface (TS): Marks the onset of a rise in sea level which can show a slight fining up pattern with the highest GR MFS lying above. Maximum Flooding Surface (MFS): Highest GR response in a marine shale at the base of a coarsening up marine package in the east above SB 3_5. These flooding surfaces are marked by high GR within tidal facies, thick undifferentiated floodplains, and single-story meandering fluvial complex in the central and western part of the basin.

Examples from stratigraphic profiles/well logs

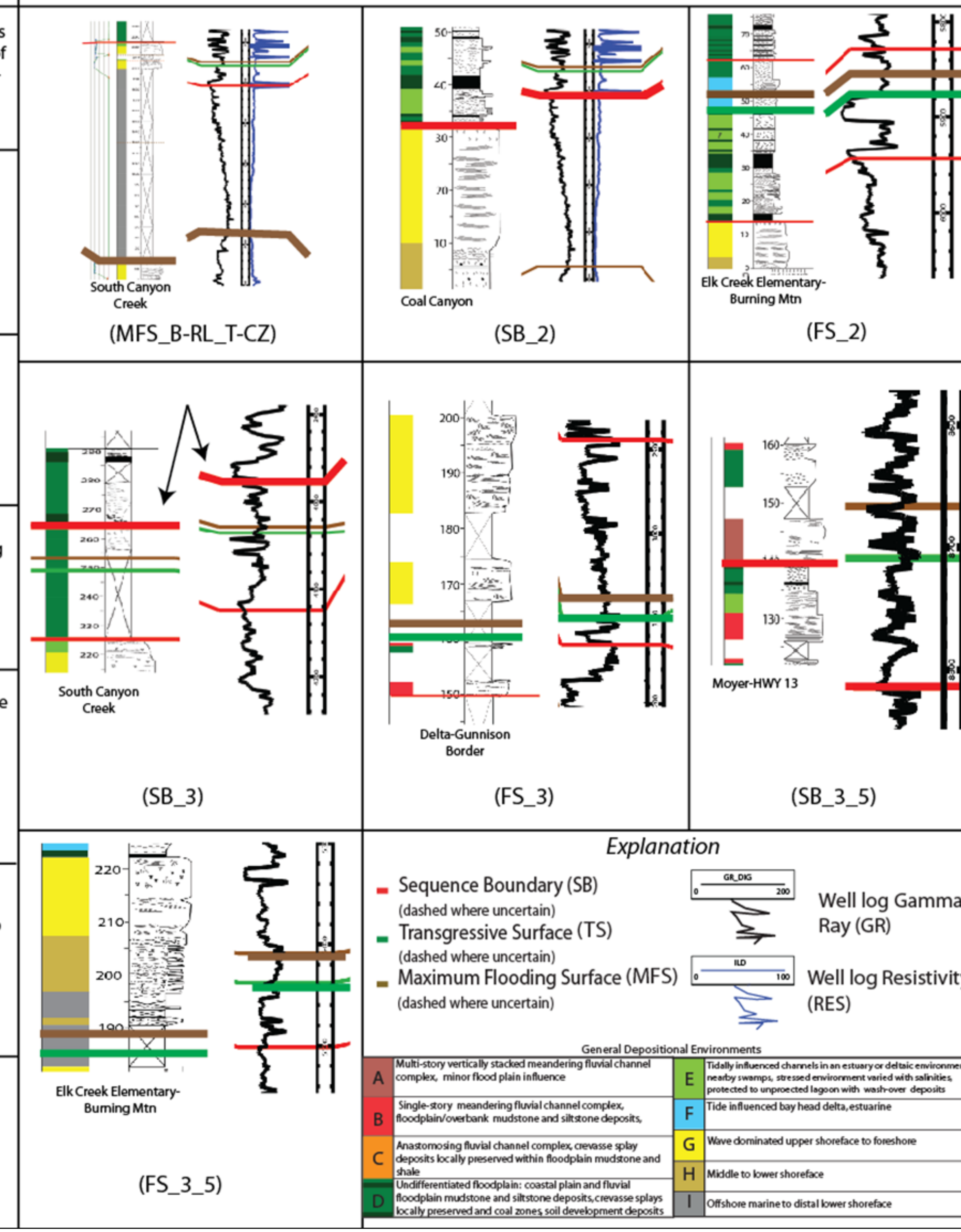


Table 1.7 Key sequence-stratigraphic surfaces described and identified in stratigraphic profiles and type well logs with an example of the criteria used to indentify these surfaces througout the basin.

Surface name	Key features for identification of surfaces
Sequence Boundary 4 (SB_4)	Chosen above FS 3_5, marked at the base of a low GR typically vertically-stacked meandering fluvial sandstone overlying more marine or tidally influenced facies in the east and undifferentiated and/or single-story meandering channels in the west.
Flooding Surface 4 (FS_4)	Transgressive Surface (TS): Marks the first onset of a landward shift in facies where marine and/or tidal facies overly continental fluvial, to undifferentiated floodplain deposits in the west and eastern parts of the basin (more coal accumulations are found in the east). Maximum Flooding Surface (MFS): Highest GR , typcially marked at the base of either a smooth coarsening up sandstone package (marine wave-dominated shoreface) in the east or a serated, coarsening up package with a sharp top (tidally influenced facies and/or bay head delta) moving to the western part of the basin.
Sequence Boundary 5 (SB_5)	Found at the base of a low GR, fining up fluvial package which overlies a coarsening up marine , tidal, or higher accomodation facies indicating a basinward shift in facies.
Flooding Surface 5 (FS_5)	Transgressive Surface (TS): In the east, this surface is picked at the base of a coarsening upward, wave-dominated marine sandstone which overlies meandering fluvial facies in the east. In the west, this surface is marked by tidal and/or high accomodation facies (coarsening up serated packages and/or high GR serated with faint fining up trends from floodplain deposits) and eventually is truncated in the west, towards the DCA. Maximum Flooding Surface (MFS): Found above FS_5_TS marking the deepest water facies (marine shale in the east to high GR floodplain deposits in the west.
Sequence Boundary 6 (SB_6)	This surface is picked at the base of a low GR, thick (10-100ft) blocky, vertically-stacked meandering fluvial sandstone complex which scours into higher accomodation settings below.
Flooding Surface 6 (FS_6)	Transgressive Surface (TS): Marked at the onset of base level rise indicating an increase in accomodation, typically above low GR packages within a high GR interval, above this surface shows serated, coarsening up packages within tidally influenced facies in the east. In the west this surface is chosen within high GR floodplain deposits with minor channelization of fluvial deposits. Maximum Flooding Surface (MFS): This surface is found at the highest GR reading directly above the FS_6_TS in either tidally influenced facies and/or within high accomodation fluvial settings such as anastomosted fluvial complexes with high crevasse splay preservation.
Sequence Boundary 7 (SB_7)	Marked above FS_6 and at the base of a thick (10-100's ft) usually blocky, low GR response well log patterns, vertically stacked meandering fluvial sandstone channels, well log pattern is dominantly comprised of these facies stacking patterns seen throughout the entire basin.

Examples from stratigraphic profiles/well logs

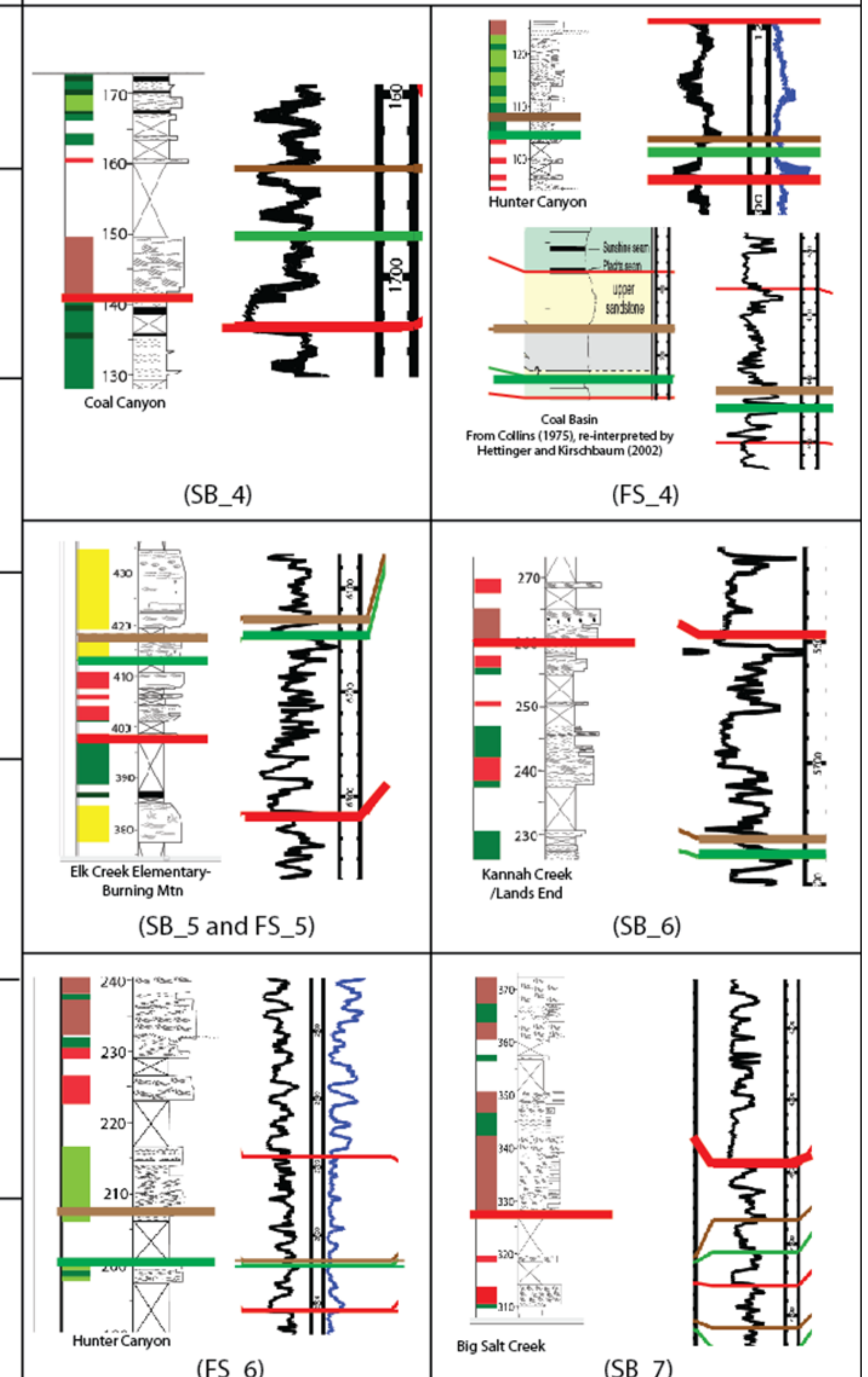
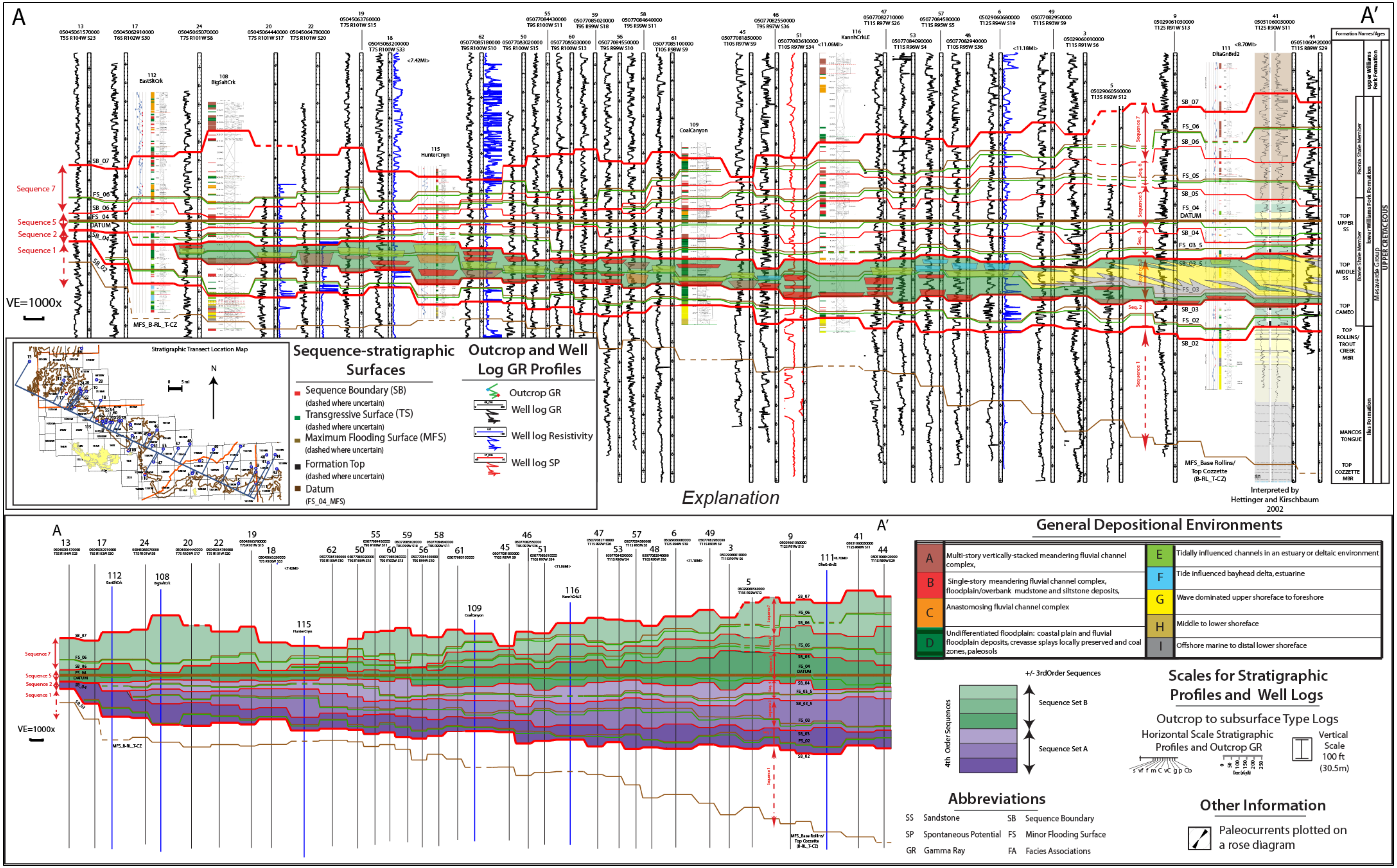


Figure 1.20 Stratigraphic transect A-A' is located in the southern part of the Piceance Basin. The transect starts in the west, near Mack, CO, and moves east, near Paonia, CO, illustrating the corellation of stratigraphic profiles and type well logs showing key sequence-stratigraphic surfaces, facies stacking patterns, and environments. The explanation beneath the correlation can be used to explain each of the following correlations (A through E) and defines the general depositonal environments , sequence stratigraphic surfaces, depositional sequences and sequence sets. Depositional sequence 3 is colored in to show the lateral variability and facies distributions observed when transitioning from the western to eastern part of the basin.



A
A'
Sequence 7
Sequence 5
Sequence 2
Sequence 1
VE=1000x
SB_07
FS_06
SB_06
FS_04
DATUM
SB_04
FS_03_5
SB_03_5
FS_03
SB_03
FS_02
SB_02
FS_05
SB_05
MFS_B-RL_T-CZ
MFS_Base Rollins/ Top Cozzette (B-RL_T-CZ)
Interpreted by Hettinger and Kirschbaum 2002
Formation Names/Ages
TOP UPPER SS
TOP MIDDLE SS
TOP CAMEO
TOP ROLLINS/ TROUT CREEK MBR
MANCOS TONGUE
TOP COZZETTE MBR
Explanation
Stratigraphic Transect Location Map
Sequence-stratigraphic Surfaces
Sequence Boundary (SB)
(dashed where uncertain)
Transgressive Surface (TS)
(dashed where uncertain)
Maximum Flooding Surface (MFS)
(dashed where uncertain)
Formation Top
(dashed where uncertain)
Datum
(FS_04_MFS)
Outcrop and Well Log GR Profiles
Outcrop GR
Well log GR
Well log Resistivity
Well log SP
General Depositional Environments
A Multi-story vertically-stacked meandering fluvial channel complex,
B Single-story meandering fluvial channel complex, floodplain/overbank mudstone and siltstone deposits,
C Anastomosing fluvial channel complex
D Undifferentiated floodplain: coastal plain and fluvial floodplain deposits, crevasse splays locally preserved and coal zones, paleosols
E Tidally influenced channels in an estuary or deltaic environment
F Tide influenced bayhead delta, estuarine
G Wave dominated upper shoreface to foreshore
H Middle to lower shoreface
I Offshore marine to distal lower shoreface
+/- 3rdOrder Sequences
Sequence Set B
Sequence Set A
4th Order Sequences
Scales for Stratigraphic Profiles and Well Logs
Outcrop to subsurface Type Logs
Horizontal Scale Stratigraphic Profiles and Outcrop GR
Vertical Scale 100 ft (30.5m)
Abbreviations
SS Sandstone
SP Spontaneous Potential
GR Gamma Ray
SB Sequence Boundary
FS Minor Flooding Surface
FA Facies Associations
Other Information
Paleocurrents plotted on a rose diagram

Figure 1.21 Stratigraphic transect B-B’ through the central part of the basin, from west to east (Fruita/Grand Junction, CO to New Castle, CO) corellating stratigraphic profiles and well logs showing depostitional environments, facies stacking patterns, and key stratigraphic surfaces through the basin. Thinning and incision occur in the west. Transitioning east shows an increase in thickness and marine-influenced facies.

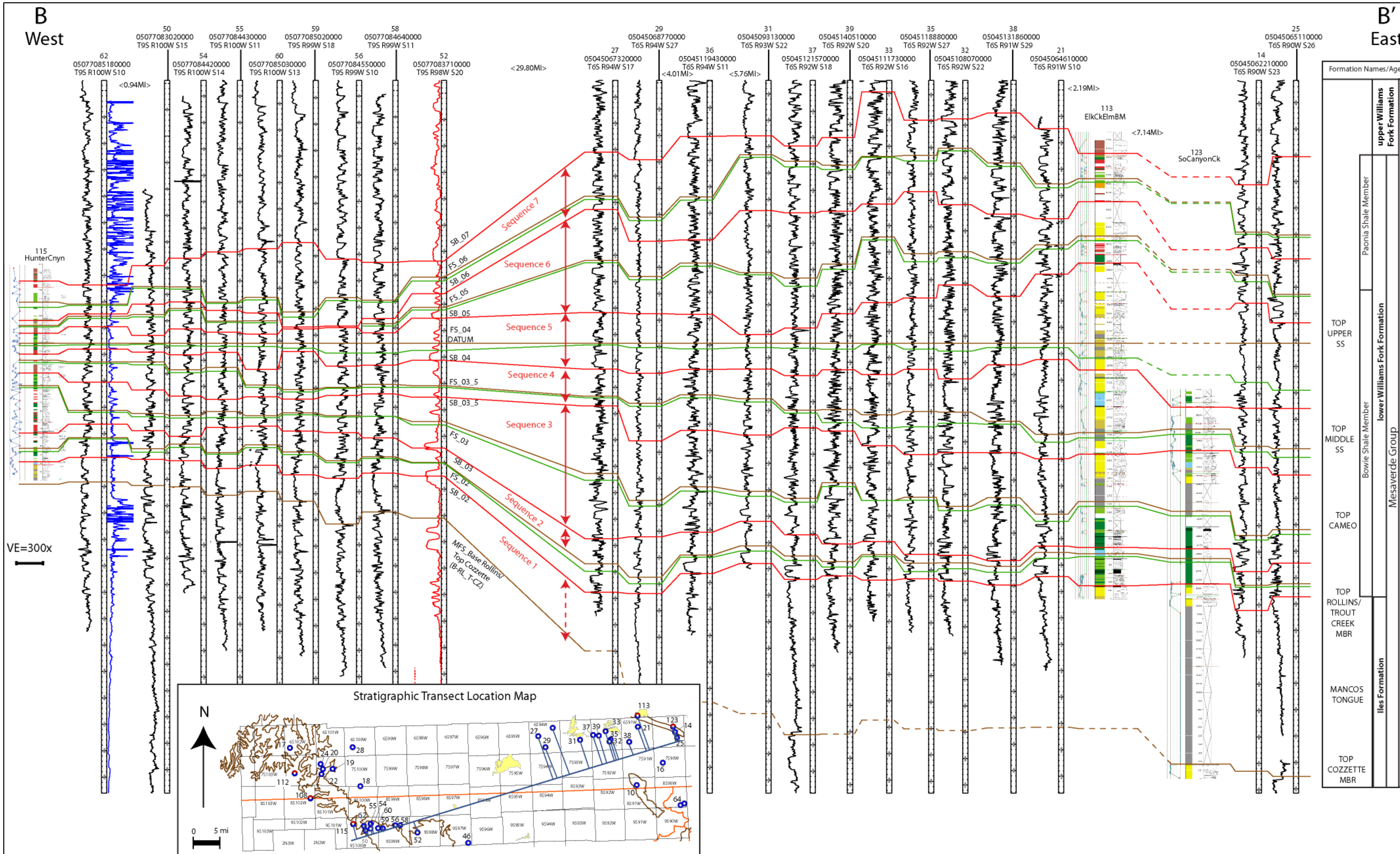

B
West
B′
East
<0.94MI>
<29.80MI>
<4.01MI>
<5.76MI>
<2.19MI>
<7.14MI>
115
HunterCnyn
113
ElkCkElmBM
123
SoCanyonCk
SB_07
FS_06
SB_06
FS_05
SB_05
FS_04
DATUM
SB_04
FS_03_5
SB_03_5
FS_03
SB_03
FS_02
SB_02
MFS_Base Rollins/
Top Cozzette
(B-RL_T-CZ)
Sequence 7
Sequence 6
Sequence 5
Sequence 4
Sequence 3
Sequence 2
Sequence 1
VE=300x
Formation Names/Ages
upper Williams Fork Formation
Paonia Shale Member
lower Williams Fork Formation
Bowie Shale Member
Iles Formation
Mesaverde Group
UPPER CRETACEOUS
TOP UPPER SS
TOP MIDDLE SS
TOP CAMEO
TOP ROLLINS/ TROUT CREEK MBR
MANCOS TONGUE
TOP COZZETTE MBR
Stratigraphic Transect Location Map
N
0
5 mi

Figure 1.22 Stratigraphic transect C-C' is located in the northern part of the basin, correlating stratigraphic profiles and well logs from west to east (Rangely, CO to Meeker, CO). Depostitional environments and key stratigraphic surfaces are shown within this transect.

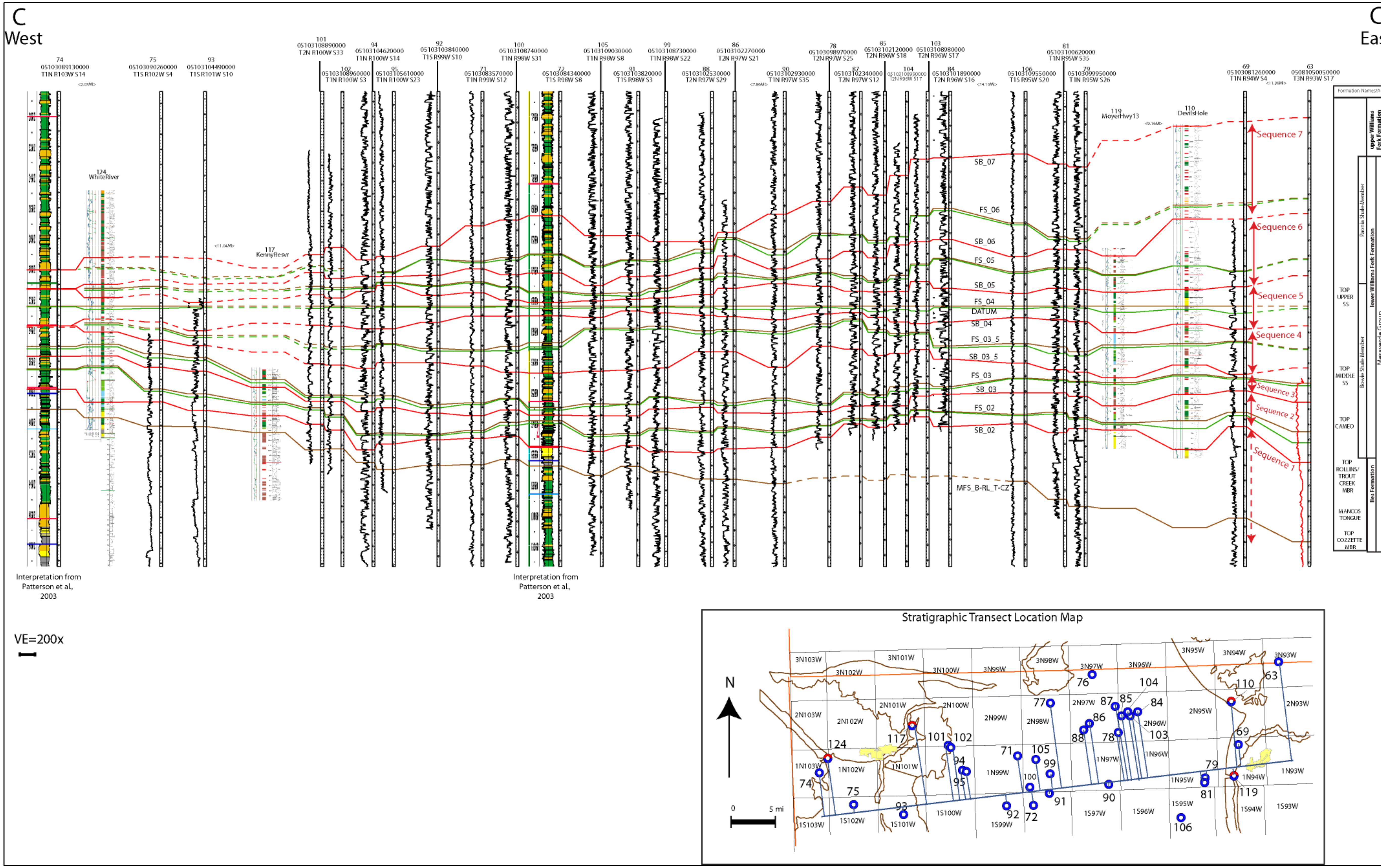
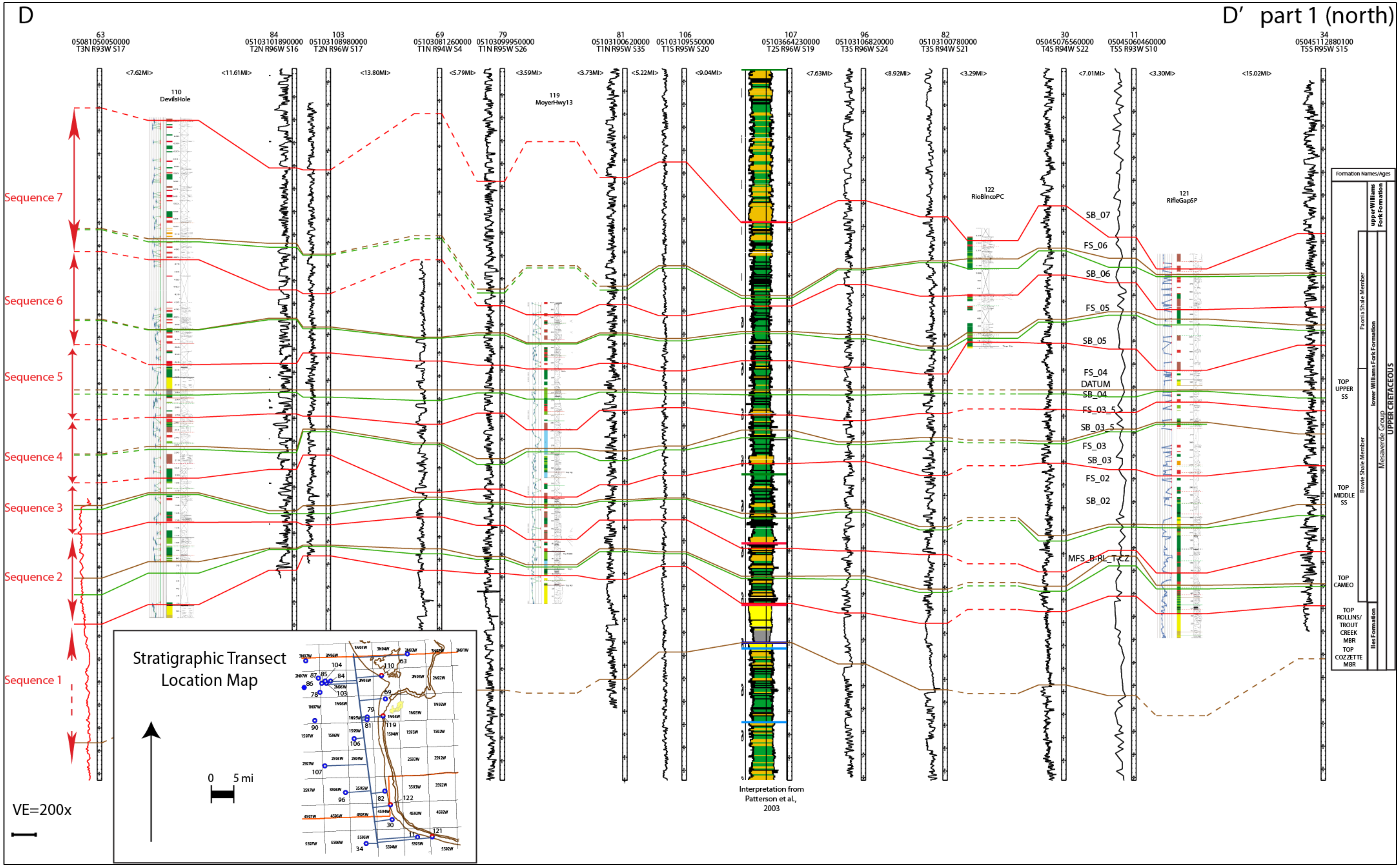
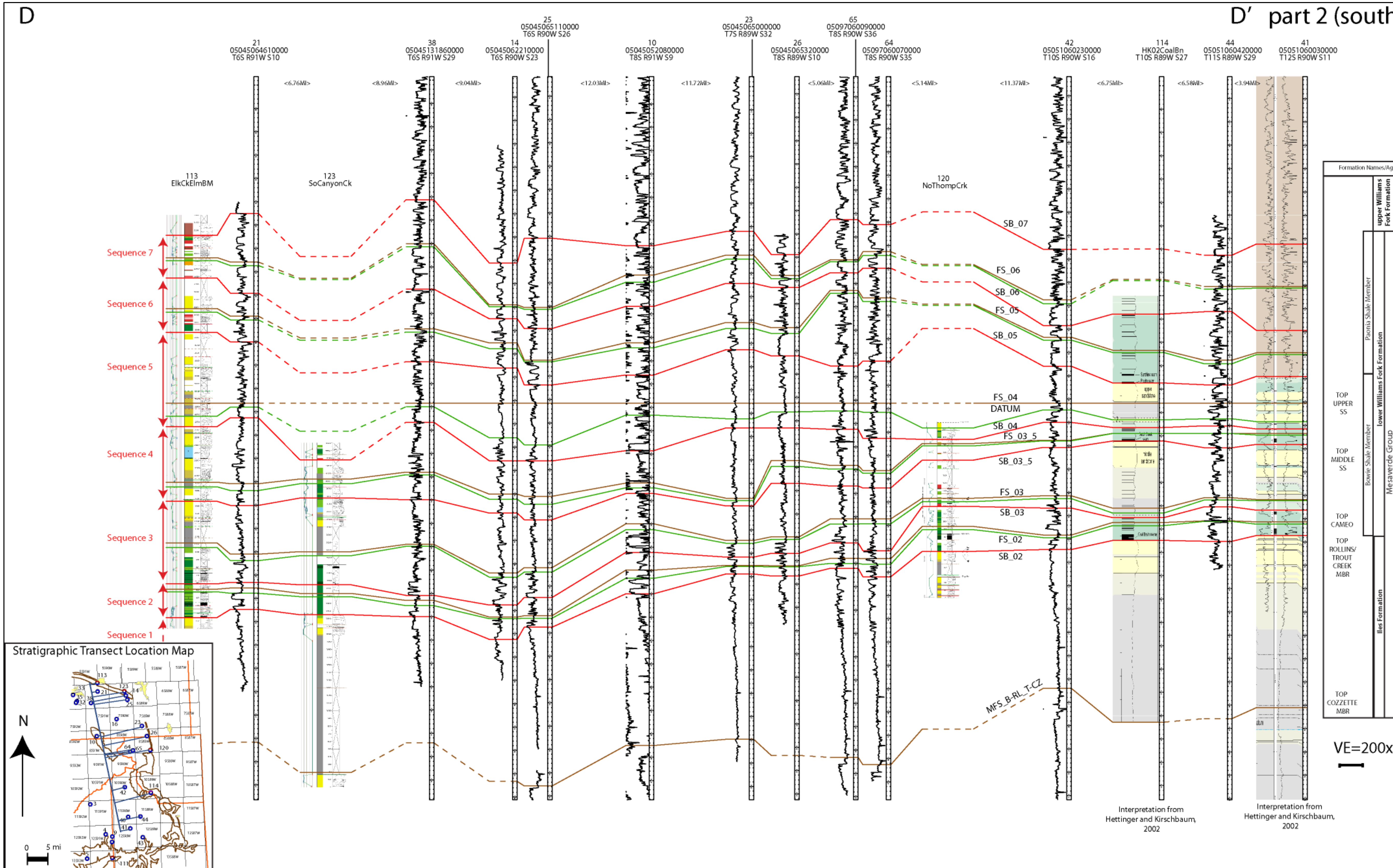

C
West
C'
East
Sequence 7
Sequence 6
Sequence 5
Sequence 4
Sequence 3
Sequence 2
Sequence 1
SB_07
FS_06
SB_06
FS_05
SB_05
FS_04
DATUM
SB_04
FS_03_5
SB_03_5
FS_03
SB_03
FS_02
SB_02
MFS_B-RL_T-CZ
WhiteRiver
KennyResvr
MoyerHwy13
DevilsHole
TOP UPPER SS
TOP MIDDLE SS
TOP CAMEO
TOP ROLLINS/ TROUT CREEK MBR
MANCOS TONGUE
TOP COZZETTE MBR
upper Williams Fork Formation
Prairie Shale Member
lower Williams Fork Formation
Bowie Shale Member
Iles Formation
Mesaverde Group
UPPER CRETACEOUS
Interpretation from Patterson et al., 2003
Interpretation from Patterson et al., 2003
VE=200x
Stratigraphic Transect Location Map
N
0
5 mi

Figure 1.23 D-D' part 1 (north) is a north to south trending stra tigraphic transect along the northeastern margin of the basin. This transect starts north of Meeker, CO and ends near Rifle Gap Reservoir State Park. This transect shows a thickening towards the north..



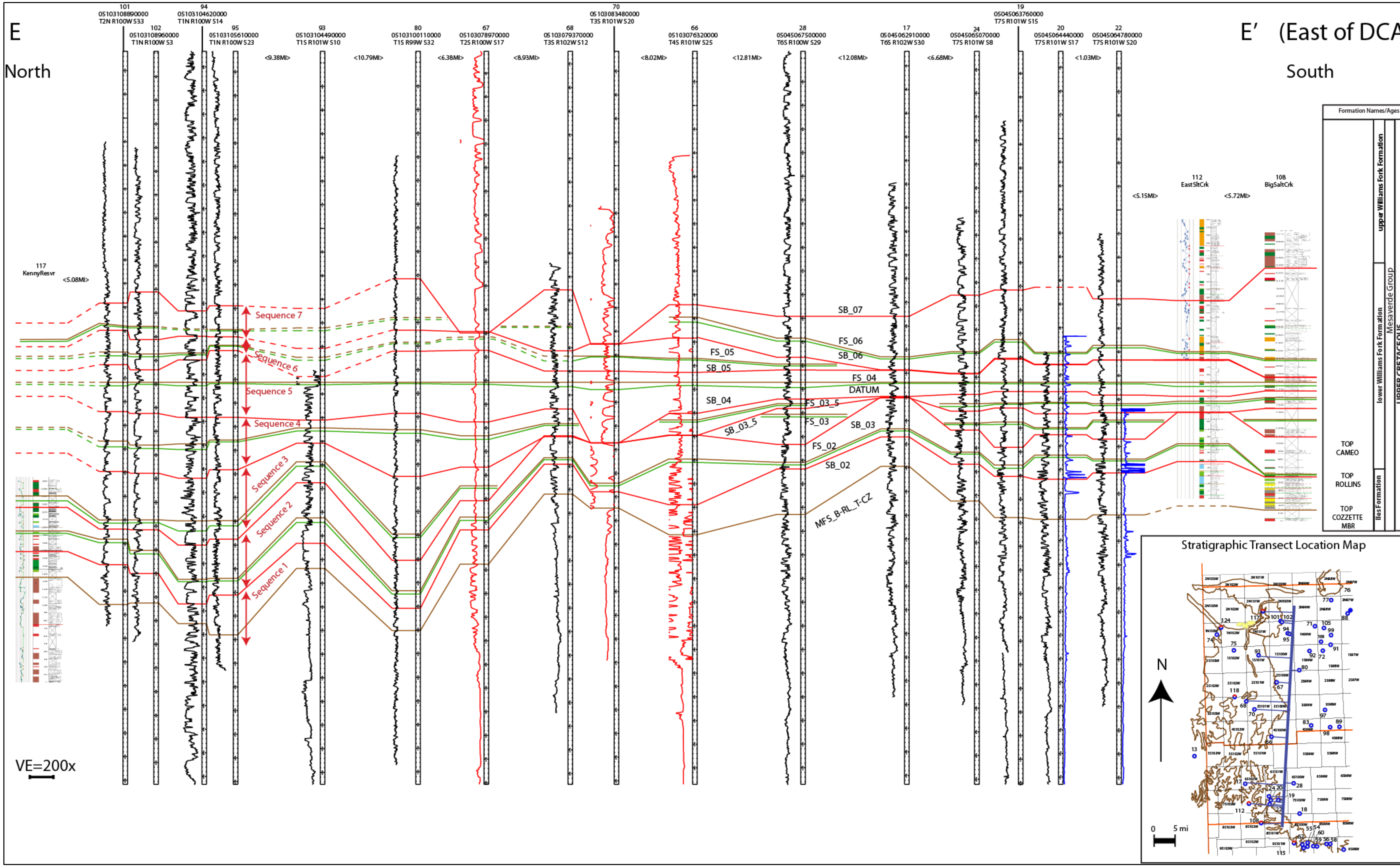
D
D' part 1 (north)
63 05081050050000 T3N R93W S17
84 05103101890000 T2N R96W S16
103 05103108980000 T2N R96W S17
69 05103081260000 T1N R94W S4
79 05103099950000 T1N R95W S26
81 05103100620000 T1N R95W S35
106 05103109550000 T1S R95W S20
107 05103664230000 T2S R96W S19
96 05103106820000 T3S R96W S24
82 05103100780000 T3S R94W S21
30 05045076560000 T4S R94W S22
11 05045060460000 T5S R93W S10
34 05045112880100 T5S R95W S15
110 DevilsHole
119 MoyerHwy13
122 RioBlncoPC
121 RifleGapSP
Sequence 7
Sequence 6
Sequence 5
Sequence 4
Sequence 3
Sequence 2
Sequence 1
SB_07
FS_06
SB_06
FS_05
SB_05
FS_04
DATUM
SB_04
FS_03_5
SB_03_5
FS_03
SB_03
FS_02
SB_02
MFS_B-BL_T-CZ
Formation Names/Ages
TOP UPPER SS
TOP MIDDLE SS
TOP CAMEO
TOP ROLLINS/ TROUT CREEK MBR
TOP COZZETTE MBR
upper Williams Fork Formation
lower Williams Fork Formation
Iles Formation
Mesaverde Group
UPPER CRETACEOUS
Interpretation from Patterson et al., 2003
Stratigraphic Transect Location Map
0 5 mi
VE=200x

Figure 1.24 D-D' part 2 (south) is a north to south trending stra tigraphic transect along the southeastern margin of the basin. This transect starts near New Castle, CO and ends near Paonia, CO. This transect also shows a thickening towards the north..



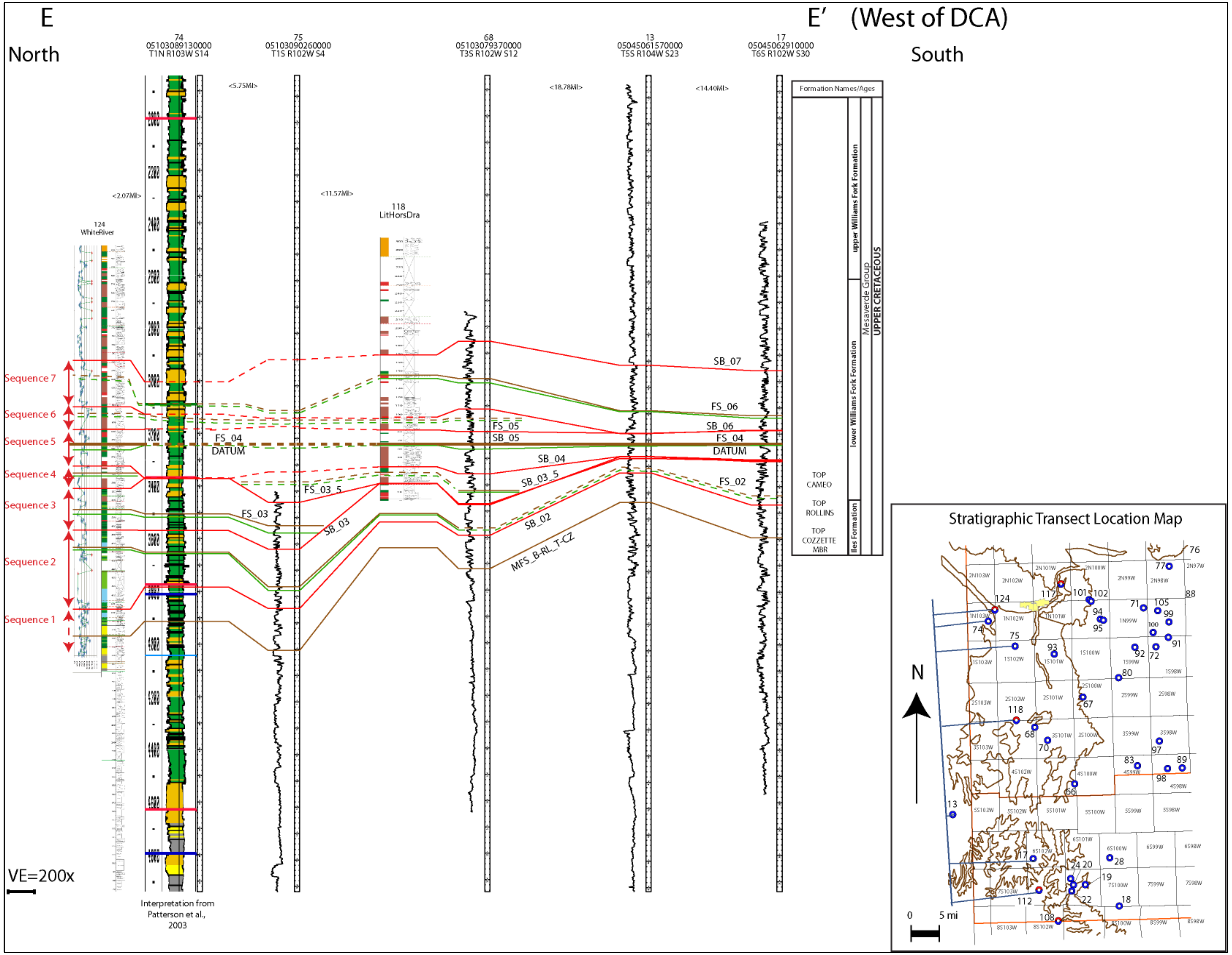
D
D' part 2 (south)
25
05045065110000
T6S R90W S26
23
05045065000000
T7S R89W S32
65
05097060090000
T8S R90W S36
21
05045064610000
T6S R91W S10
38
05045131860000
T6S R91W S29
14
05045062210000
T6S R90W S23
10
05045052080000
T8S R91W S9
26
05045065320000
T8S R89W S10
64
05097060070000
T8S R90W S35
42
05051060230000
T10S R90W S16
114
HK02CoalBn
T10S R89W S27
44
05051060420000
T11S R89W S29
41
05051060030000
T12S R90W S11
113
ElkCkElmBM
123
SoCanyonCk
120
NoThompCrk
Sequence 7
Sequence 6
Sequence 5
Sequence 4
Sequence 3
Sequence 2
Sequence 1
SB_07
FS_06
SB_06
FS_05
SB_05
FS_04
DATUM
SB_04
FS_03_5
SB_03_5
FS_03
SB_03
FS_02
SB_02
MFS_B-RL_T-CZ
Formation Names/Ages
upper Williams Fork Formation
Paonia Shale Member
lower Williams Fork Formation
Bowie Shale Member
Mesaverde Group
UPPER CRETACEOUS
Iles Formation
TOP UPPER SS
TOP MIDDLE SS
TOP CAMEO
TOP ROLLINS/ TROUT CREEK MBR
TOP COZZETTE MBR
VE=200x
Interpretation from Hettinger and Kirschbaum, 2002
Interpretation from Hettinger and Kirschbaum, 2002
Stratigraphic Transect Location Map
N
0 5 mi

Figure 1.25 E-E' east of Douglas Creek Arch (DCA) is a north to south trending stratigraphic transect along the western margin of the basin. This transect starts near Rangely, CO and ends near Mack, CO. This transect is high complicated due to the proximity to the DCA structure. Incision, onlapping trends, and truncation were identified near data points 67, 70 and 17. This correlation suggests that the DCA was uplifting during the time of deposition of the lower Williams Fork Formation. This section is not a stratigraphic dip orientation and some of the data points which show these folding features in the north can be located further off structure than others.



E
E′ (East of DCA)
North
South
Sequence 7
Sequence 6
Sequence 5
Sequence 4
Sequence 3
Sequence 2
Sequence 1
SB_07
FS_06
SB_06
FS_05
SB_05
FS_04
DATUM
SB_04
FS_03_5
SB_03_5
FS_03
SB_03
FS_02
SB_02
MFS_B-RL_T-CZ
TOP CAMEO
TOP ROLLINS
TOP COZZETTE MBR
Formation Names/Ages
upper Williams Fork Formation
lower Williams Fork Formation
Iles Formation
Mesaverde Group
UPPER CRETACEOUS
VE=200x
Stratigraphic Transect Location Map
N
0 5 mi

Figure 1.26 E-E' west of Douglas Creek Arch (DCA) is a north to south trending stratigraphic transect along the western margin of the basin. This transect also starts near Rangely, CO and ends near Mack, CO, however it runs along the western side of the DCA structure. This transect shows an overall thinning to the south, towards the Book Cliffs and a thickening to the north. Data points 68 and 13 show areas of the most incision and thinning.


E
North
E′ (West of DCA)
South
74
05103089130000
T1N R103W S14
75
05103090260000
T1S R102W S4
68
05103079370000
T3S R102W S12
13
05045061570000
T5S R104W S23
17
05045062910000
T6S R102W S30
124
WhiteRiver
118
LitHorsDra
Formation Names/Ages
upper Williams Fork Formation
lower Williams Fork Formation
Iles Formation
Mesaverde Group
UPPER CRETACEOUS
TOP CAMEO
TOP ROLLINS
TOP COZZETTE MBR
Sequence 7
Sequence 6
Sequence 5
Sequence 4
Sequence 3
Sequence 2
Sequence 1
SB_07
FS_06
SB_06
FS_05
SB_05
FS_04
DATUM
SB_04
SB_03_5
FS_03_5
FS_03
SB_03
FS_02
SB_02
MFS_B-RL_T-CZ
VE=200x
Interpretation from Patterson et al., 2003
Stratigraphic Transect Location Map
N
0
5 mi

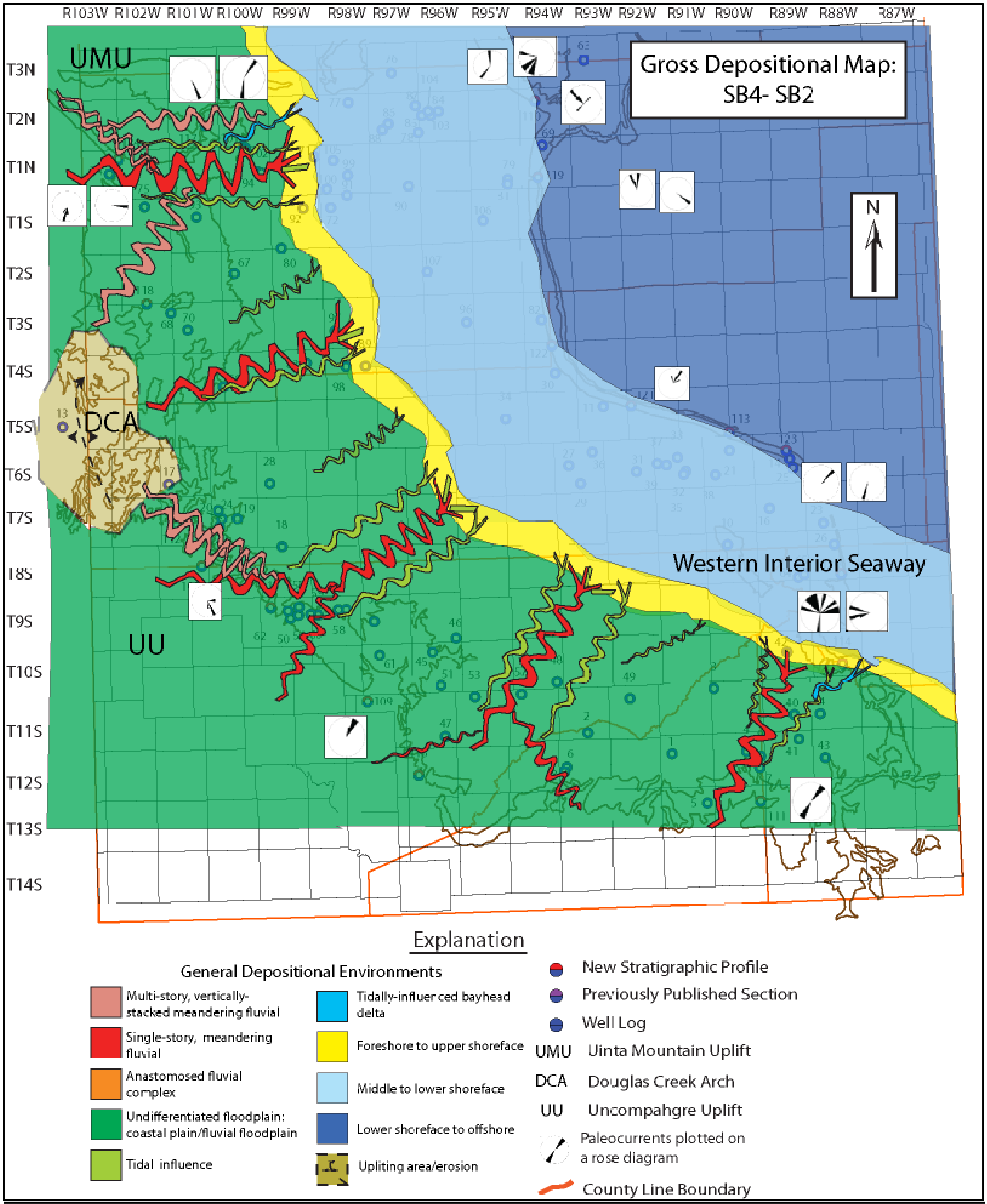


Figure 1.27 Gross depositional map of sequence set A (SB4-SB2) illustrating the geospatial changes observed when moving from the western to eastern part of the Piceance Basin.

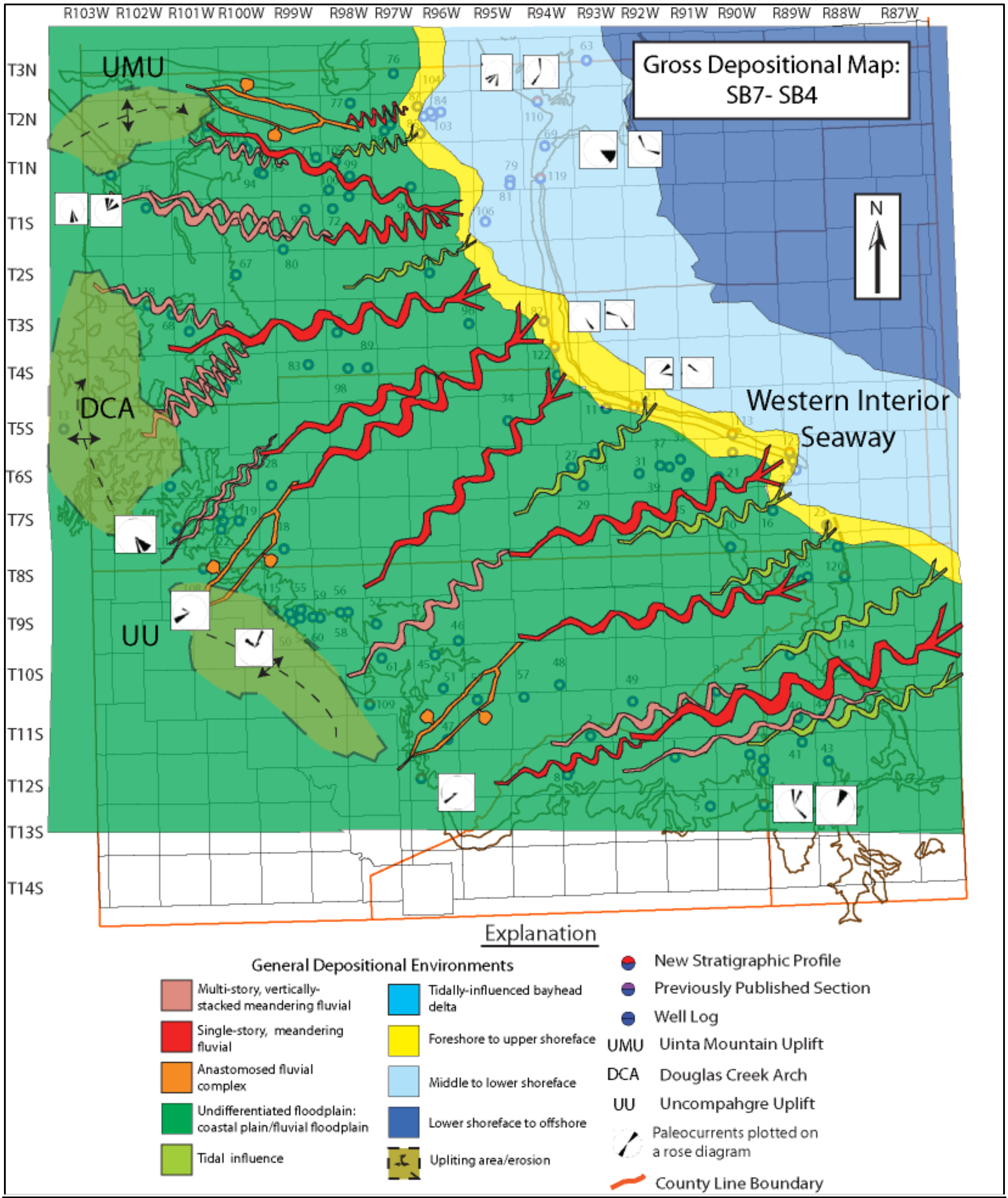


Figure 1.28 Gross depositional map of sequence set B (SB7-SB4) illustrating the geospatial changes observed when moving from the western to eastern part of the Piceance Basin.

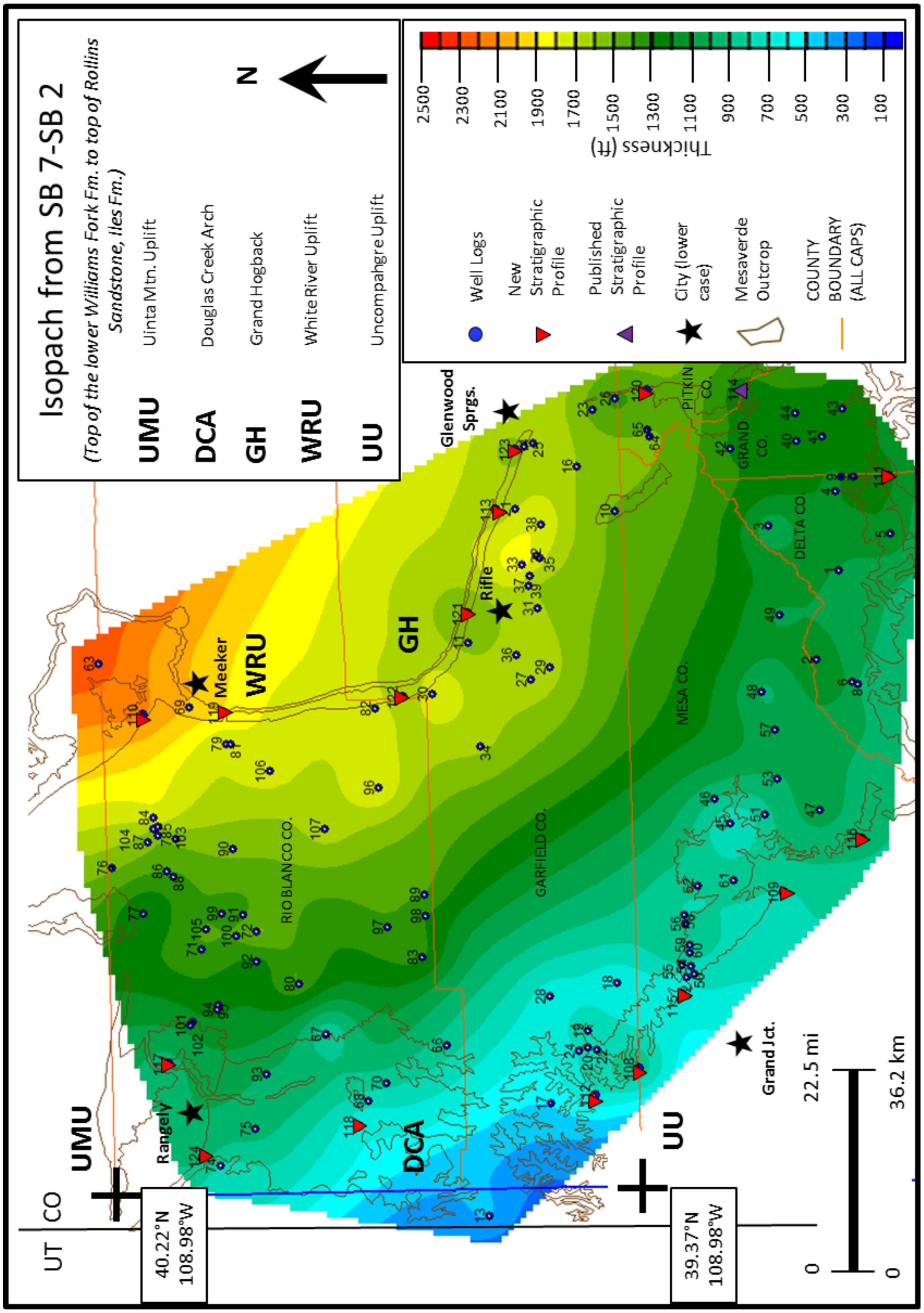


Figure 1.29 Isopach map of the total stratigraphic study interval, from sequence boundary 7 to sequence boundary 2 (SB 7- SB 2). The color scale for isopach thickness ranges from 100 ft to 2500 ft or blue to red respectively.

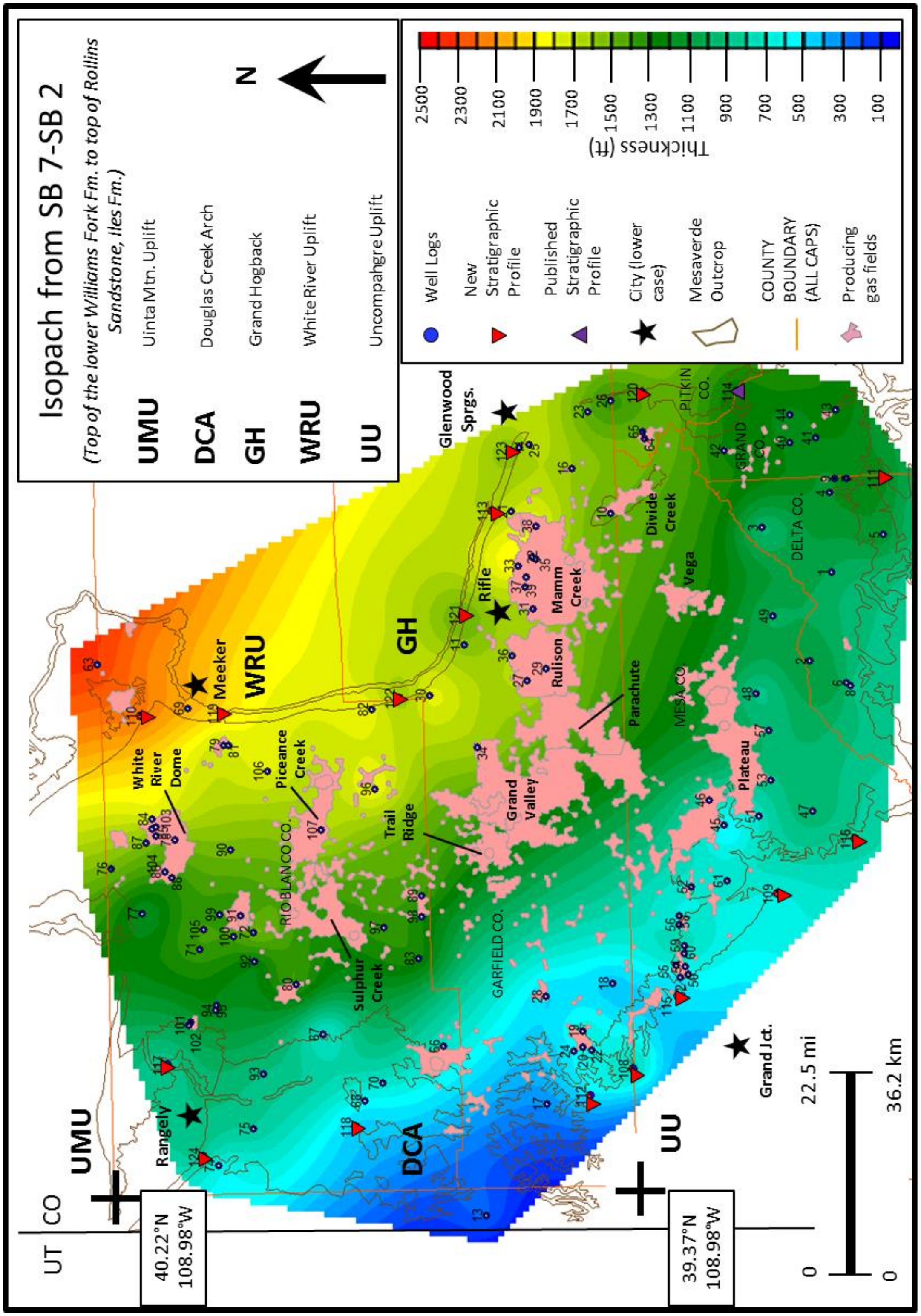


Figure 1.30 Isopach map of the total stratigraphic interval (SB7 to SB 2) with known gas producing fields in pink.

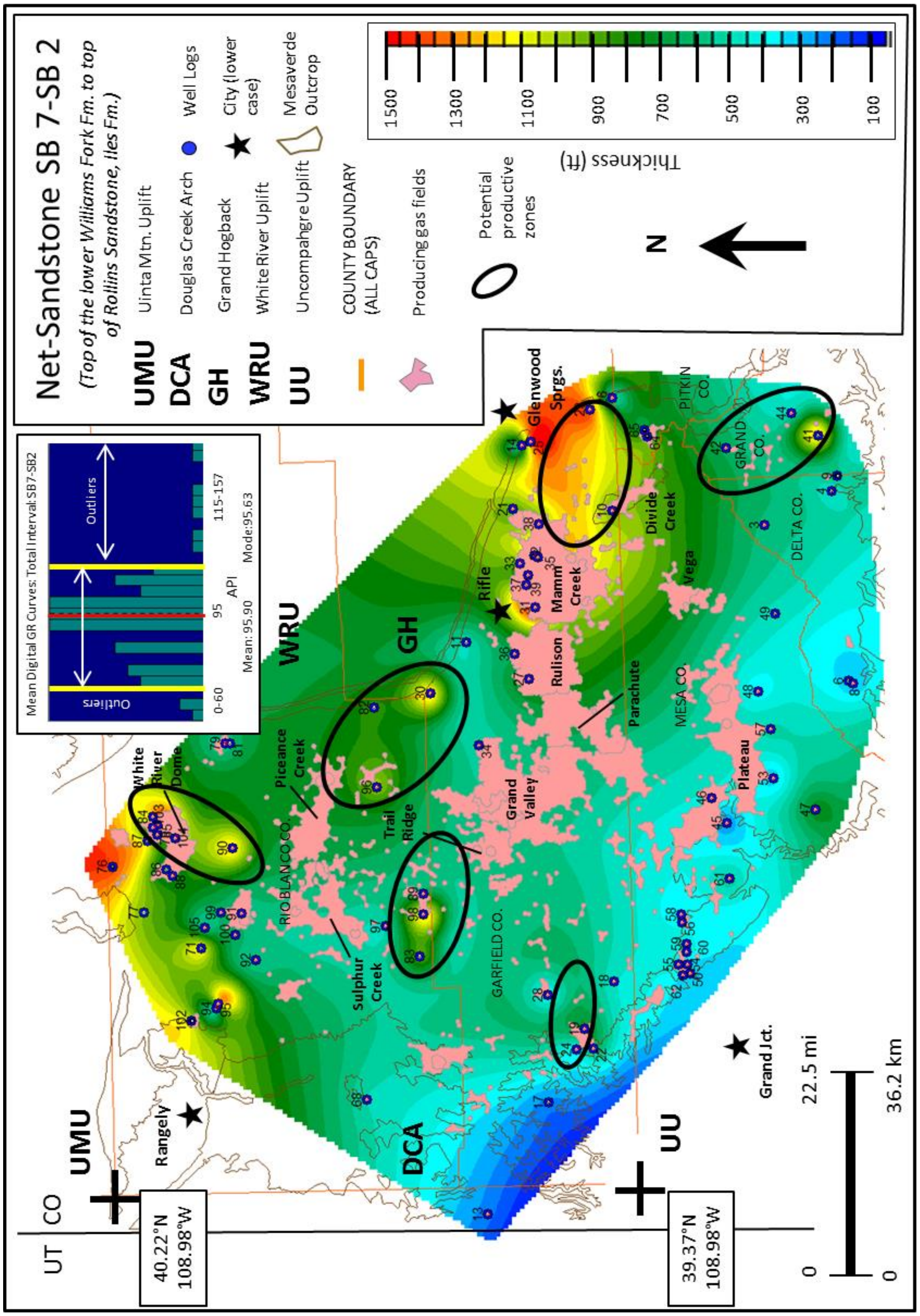


Figure 1.31 Net-sandstone map of the total stratigraphic interval (SB7 to SB 2). The histogram illustrates how the cutoffs were applied to the GR curves utilized in this study which was averaged at 95 API units. The color range for the net-sandstone thickness ranges from 100 to 1500 ft thick (blues represent low net-sandstone accumulation and reds indicate high net-sandstone accumulation). Pink polygons represent producing gas fields which can sometimes correspond with some of the high net-sandstone accumulations.

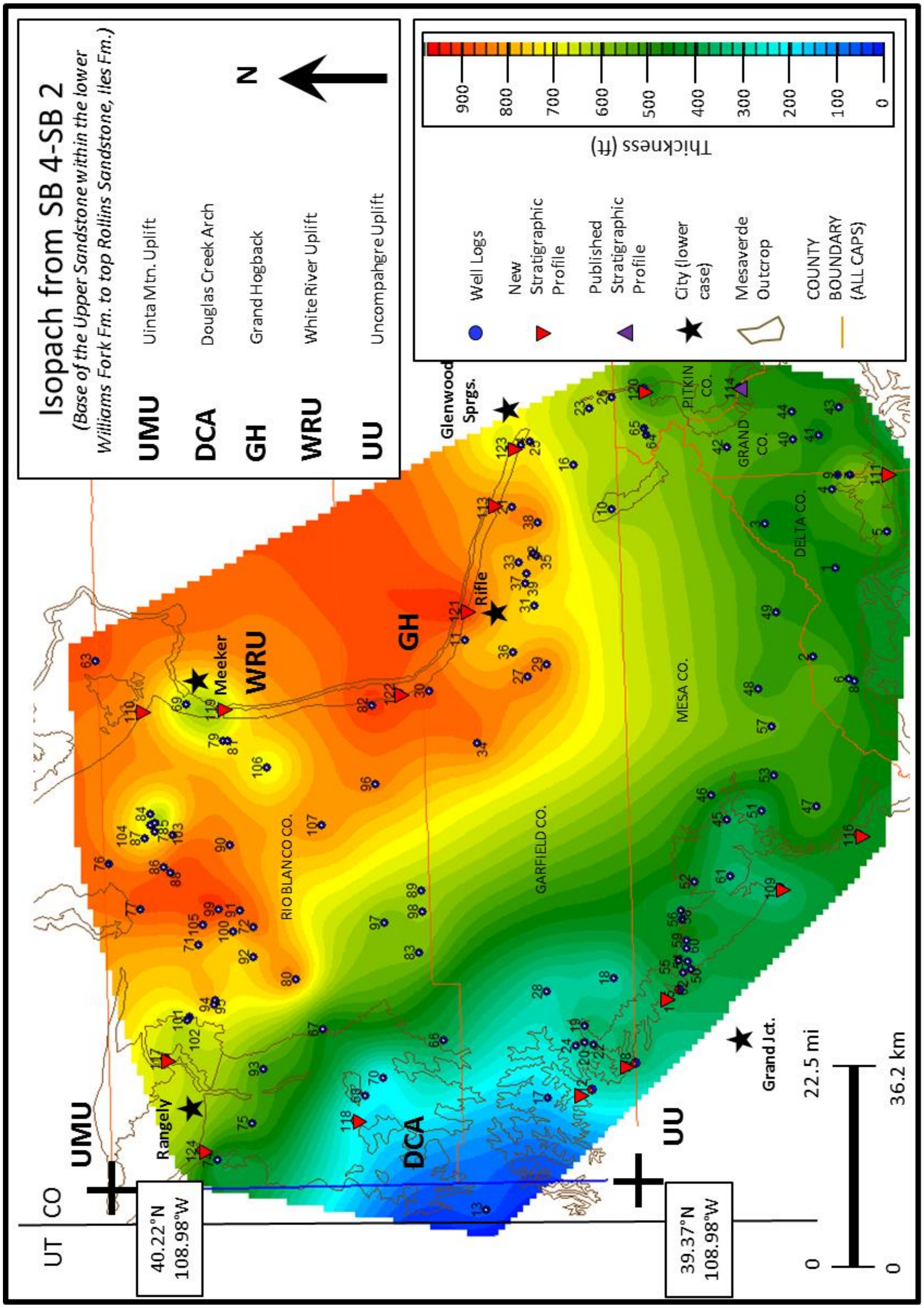


Figure 1.32 Isopach map of sequence set A (SB4 to SB 2). The stacking patterns within this sequence set are progradational. The color range for the thickness values range from 0 to 900 ft thick.

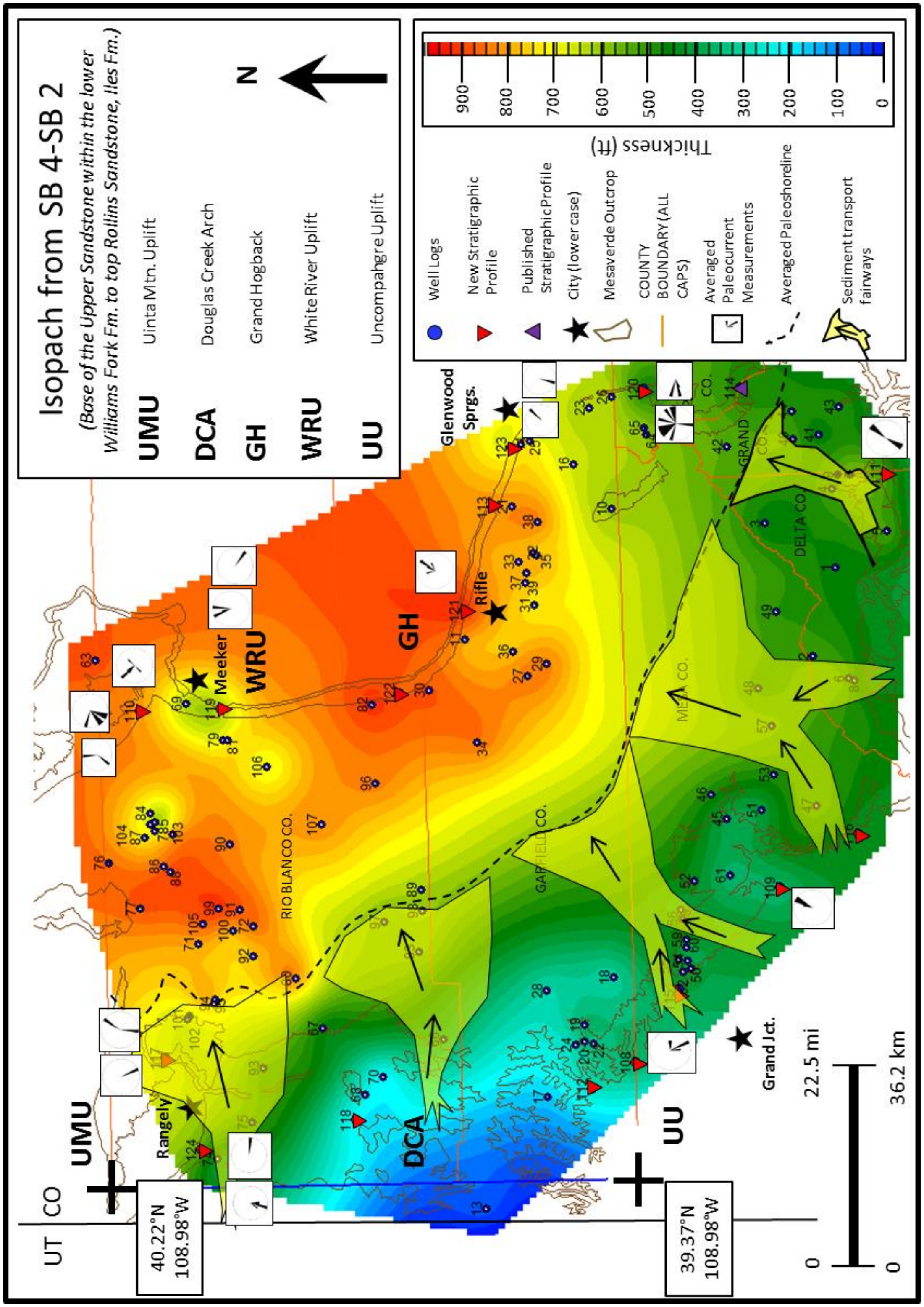


Figure 1.33 Isopach map of sequence set A (SB4 to SB 2). The dashed black line represents an average location and orientation of the paleoshoreline. The yellow polygons represent drainage areas and sediment fairways. stacking patterns within this sequence set are progradational. The color range for the thickness values range from 0 to 900 ft thick.

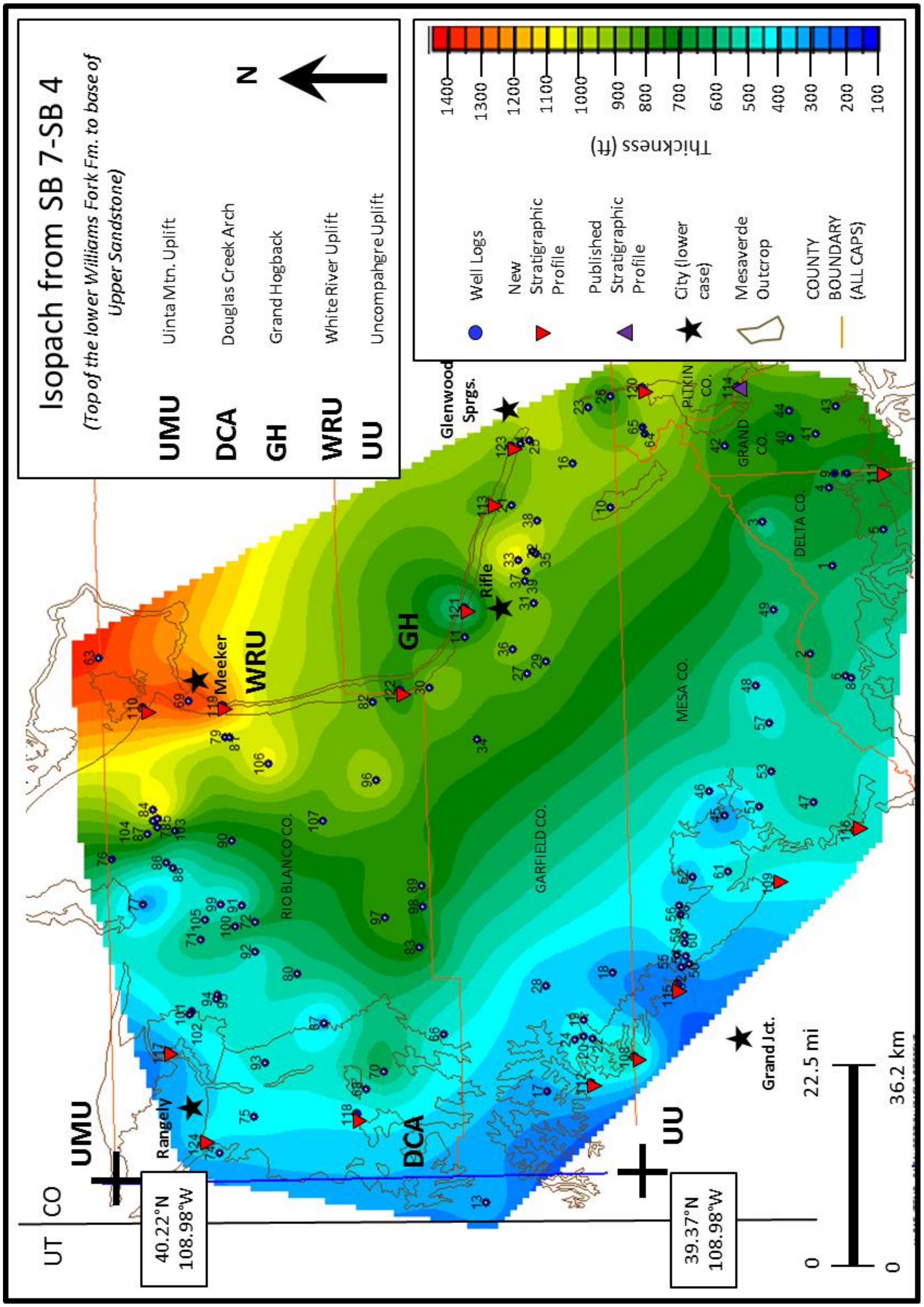


Figure 1.34 Isopach map of sequence set B (SB7 to SB 4). The stacking patterns within this sequence set are more aggradational. The color range for the thickness values range from 100 to 1400 ft thick.

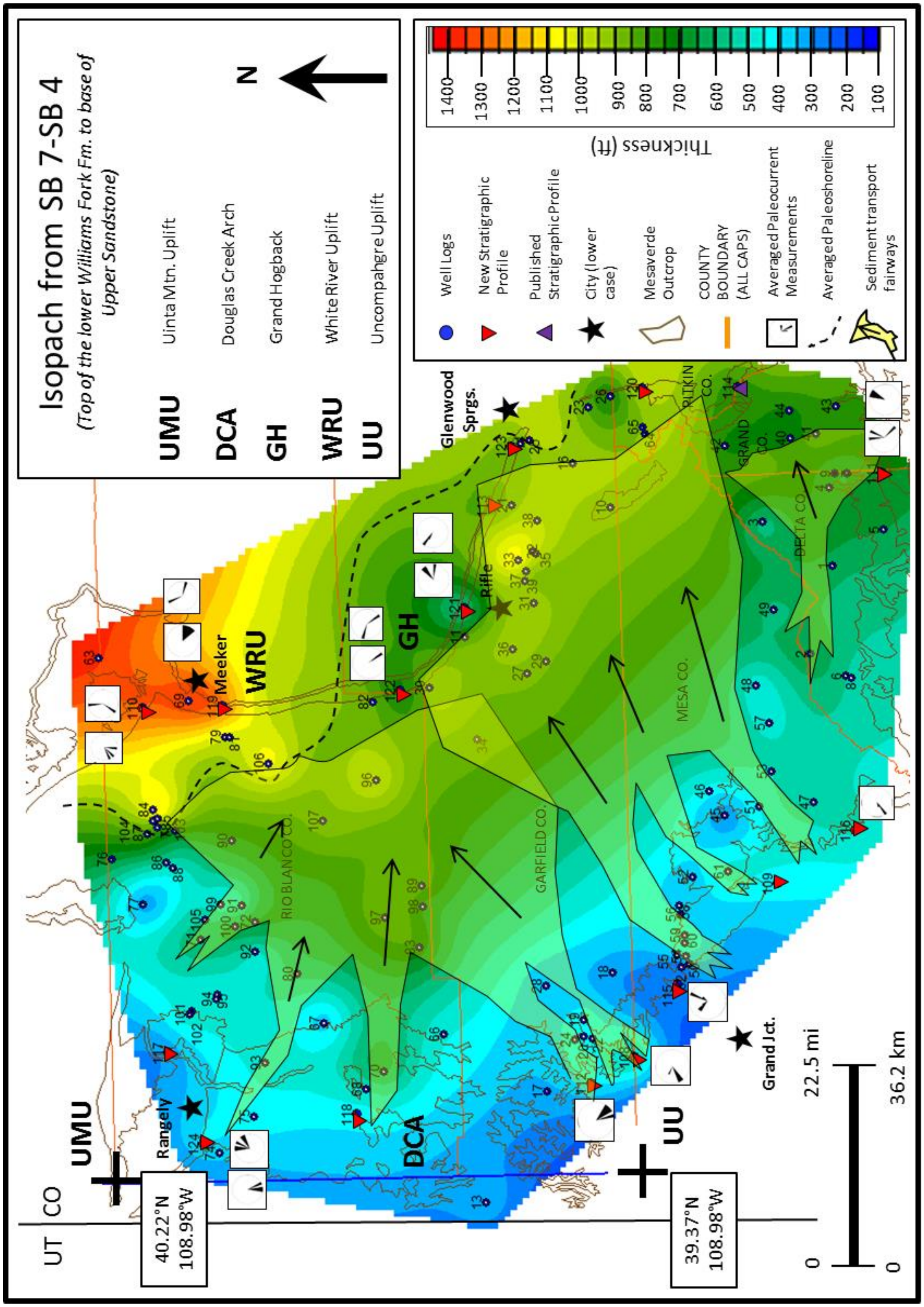


Figure 1.35 Isopach map of sequence set B (SB7 to SB 4). The dashed black line represents an average location and orientation of the paleoshoreline. The yellow polygons represent drainage areas and sediment fairways and average paleoflow directions. The color range for the thickness values range from 100 to 1400 ft thick.

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